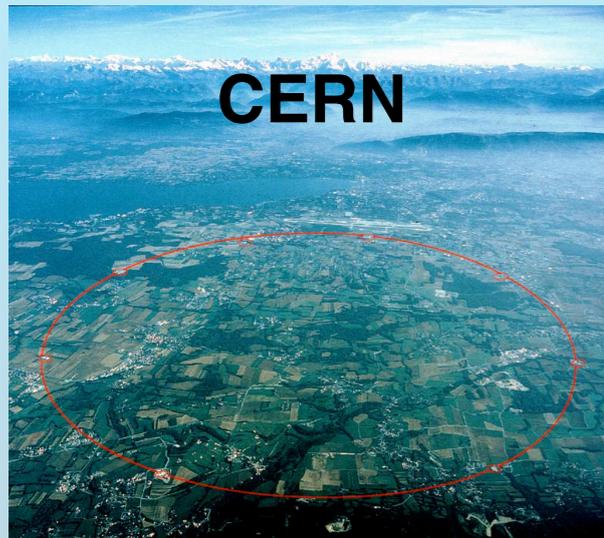


GLACIER for LBNO: Physics goals and R&D results

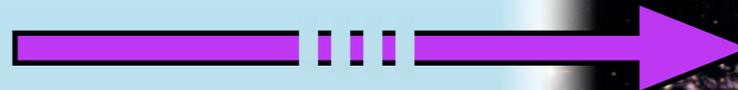
Sebastien Murphy ETH Zürich

on behalf of the Laguna/LBNO collaboration

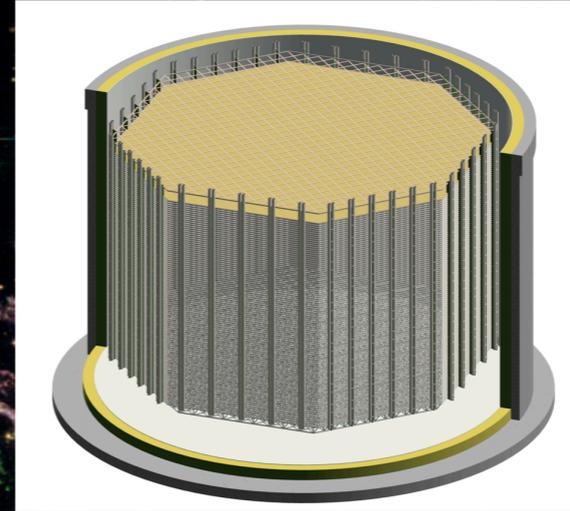
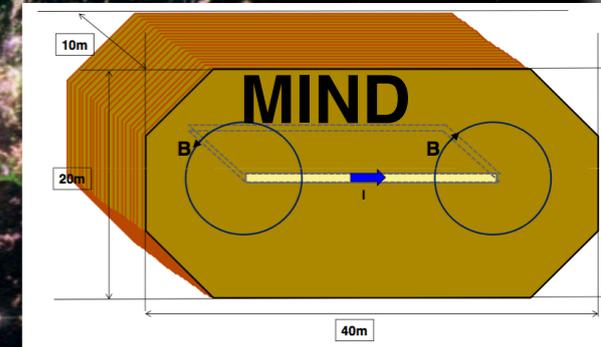


CERN

2300 km



GLACIER 20kt,50 kt

deep
underground

LAGUNA

Deep underground neutrino observatory

neutrino beam + near detector

*wide band ν_μ beam $\sim 1-10$ GeV \Rightarrow
covers 2 oscillation maximums

~ 4 and ~ 1.5 GeV

*SPS protons @ 400 GeV

*SPS upgrade 800 GeV 2 MW

*Near detector:

HpAr TPC + magnetized iron
detector (MIND)

*Giant double-phase LAr TPC+
magnetized iron detector (MIND)

*Neutrinos from MeV to 10's GeV
(supernovae, reactors, solar,
atmospheric..)

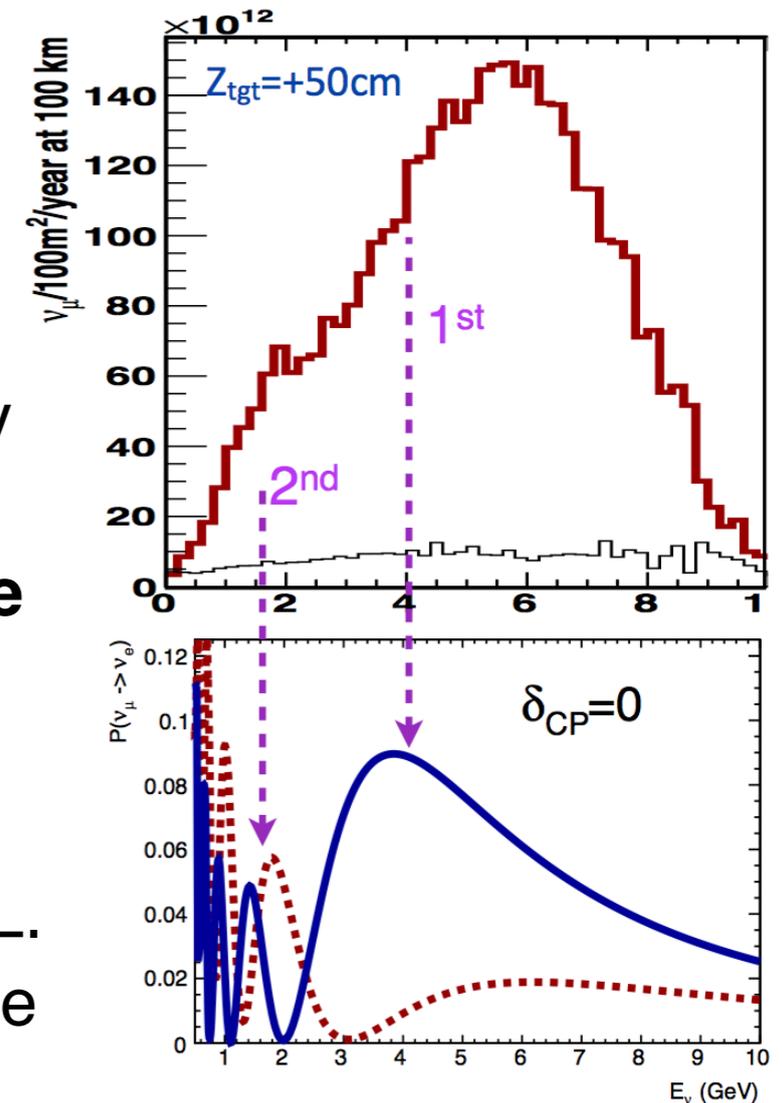
*Address questions of particle and
astroparticle physics

*Proton decay

LBNO: Neutrino oscillations \rightarrow MH, CPV, precision measurements

Long baseline neutrino oscillation

- * $\nu_\mu \rightarrow \nu_e, \nu_\mu \rightarrow \nu_\tau, \nu_\mu \rightarrow \nu_\mu$ & ν_{NC}
- * study the L/E feature of the oscillation induced by matter effects and CP-phase terms, independently for ν and anti- ν , by direct measurement of event spectrum which covers the **first and second oscillation maxima thanks to the long baseline**
- * Mass Hierarchy determination @ 5σ C.L in first two year of running.
- * CP-phase measurement 1st phase 60% coverage @90%C.L. CPV @ 5σ C.L with upgrades to increase statistical significance of 2nd maximum.
- * Test of 3 generation mixing



optimise beam(horns, target position ...) to cover 1st and 2nd osc. max

Astrophysics program

- * extended nucleon decay search: probe BSM physics up to GUT scale
- * Astrophysical and atmospheric neutrino detection

Long baseline neutrino oscillation

* $\nu_\mu \rightarrow \nu_e, \nu_\mu \rightarrow \nu_\tau, \nu_\mu \rightarrow \nu_\mu$ & ν_{NC}

* study the L/E feature of the oscillation induced by matter effects and CP-phase terms, independently for ν and $\bar{\nu}$
 direct measurement of event spectrum which covers

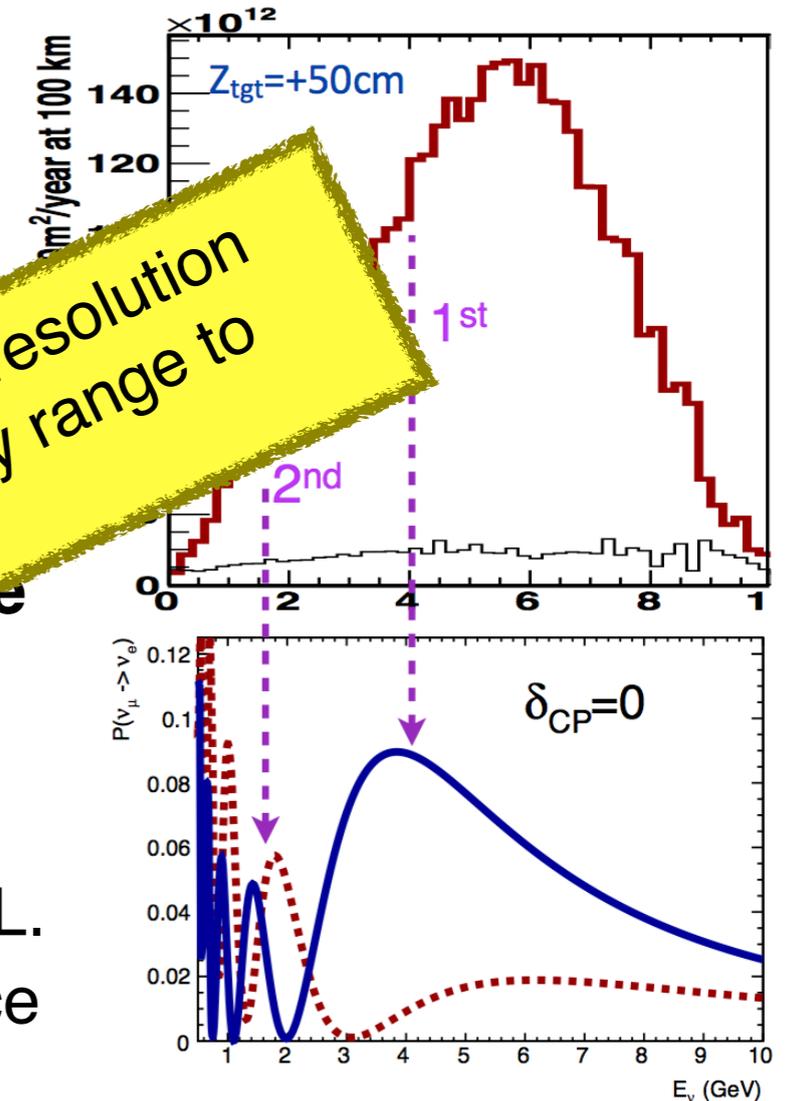
and second oscillation maxima thanks to

* Mass Hierarchy determination with 90% coverage @90%C.L. after 1 year of running.

* CP-phase measurement with 90% coverage @90%C.L. with 1 year of running
 CPV @ 5σ C.L with 1 year of running
 of 2nd maximum.

* Test of 3 generation mixing

A detector with large mass, excellent energy resolution and tracking performance over a wide energy range to "see" shape of the oscillated spectra



optimise beam(horns, target position ...) to cover 1st and 2nd osc. max

Astrophysics program

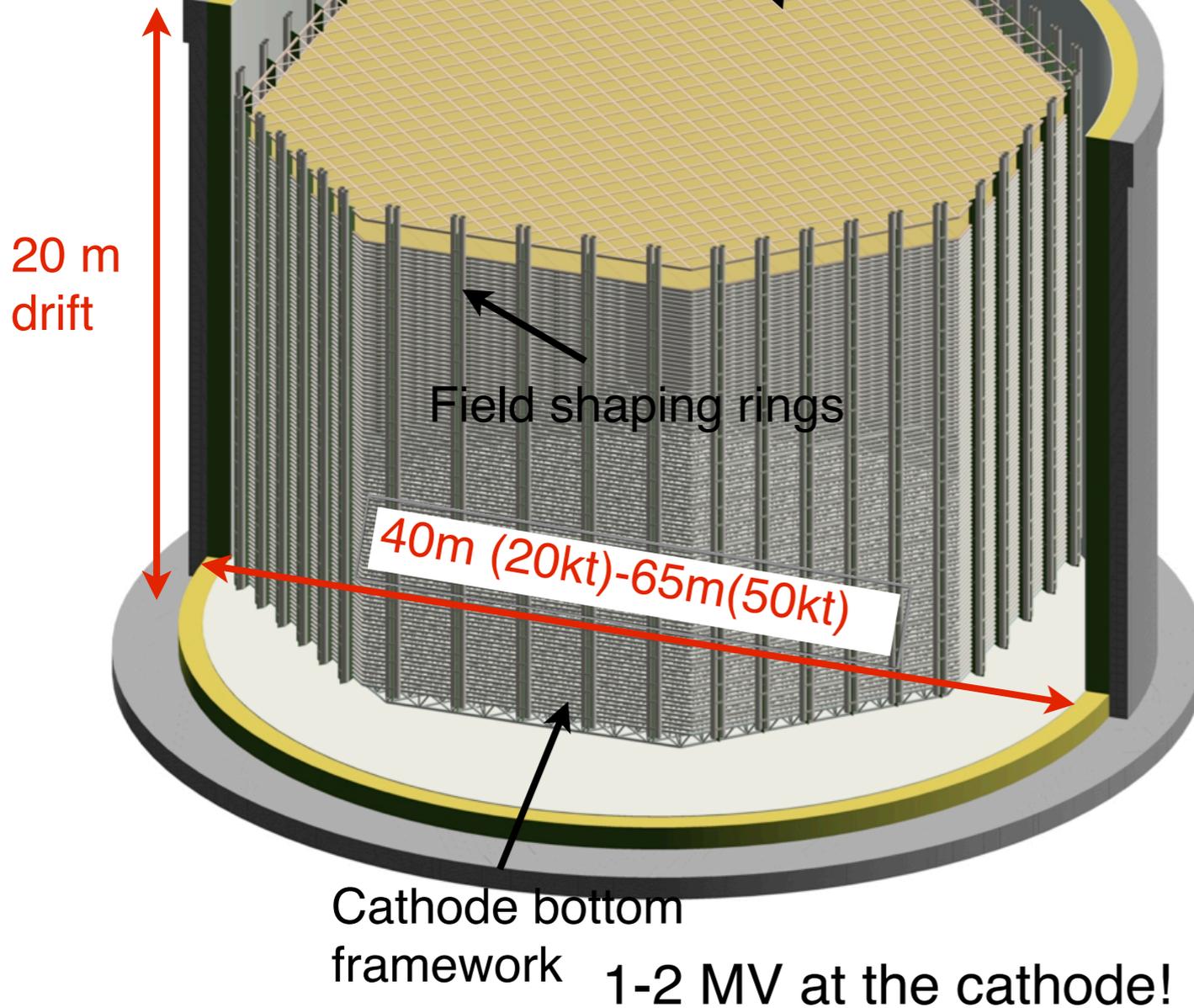
* extended nucleon decay search: probe BSM physics up to GUT scale

* Astrophysical and atmospheric neutrino detection

Giant Liquid Argon Charge Imaging expERiment

GLACIER 20kt, 50kt Giant double phase LAr TPC

Charge Readout Plane (CRP)

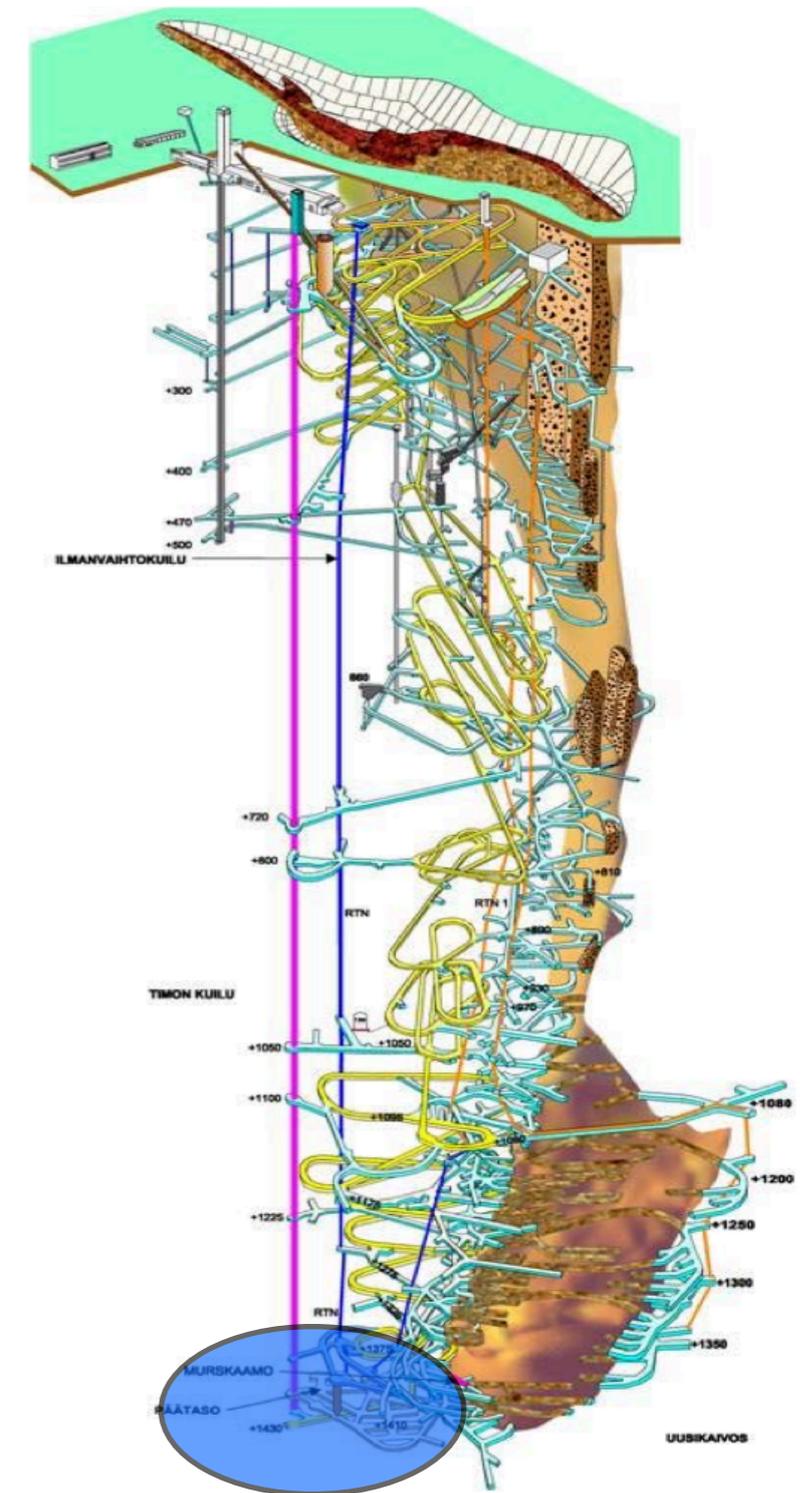


	20KT	50KT
Liquid argon density at 1.2 bar [T/m ³]	1.38346	
Full LAr height [m]	22	
Instrumented LAr height [m]	20	
Pressure on the bottom due to LAr [T/m ²]	30.4 (= 0.3 MPa = 3 bar)	
Vessel diameter [m]	37	55 76
Vessel base surface [m ²]	1'075.2	2'375.8 4'536.5
Instrumented LAr area (percentage) [m ²]	824 (77%) (76.6%)	1'845 (78%) 3'634 (80.1%)
Liquid argon volume [m ³]	23'654.6	52'268.2 99'802.1
Instrumented LAr mass [KT]	22.799	51.299 100.550
Charge readout square panels (1m×1m option)	804	1'824 14'456
Charge readout triangular panels (0.5m ²)	40	60
Charge readout square panels (4m×4m option)	40	104
Charge readout triangular panels (2m ²)	20	16
Number of signal feed-throughs (666 ch/FT)	416	1'028 1'872
Number of PMTs (1m × 1m option)	~800	~1'850 909
Number of PMTs (1.2m × 1.2m option)		~1'288
Number of PMTs (2m × 2m option)	~200	~450
Number of field shaping rings	100	
Vertical spacing (heart to heart distance) of field shaping rings [mm]	200	



Extremely convenient site:

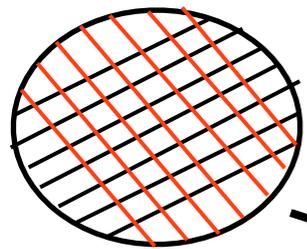
- Deepest mine in Europe: ~1400 m, 4000 m.w.e
- Baseline from CERN 2300 km
- lowest reactor neutrino background in Europe
- efficient infrastructures and excavation aspects
- Interesting distance from other potential neutrino sources
 DESY(1500km), Protvino(1160km), RAL(2300km)



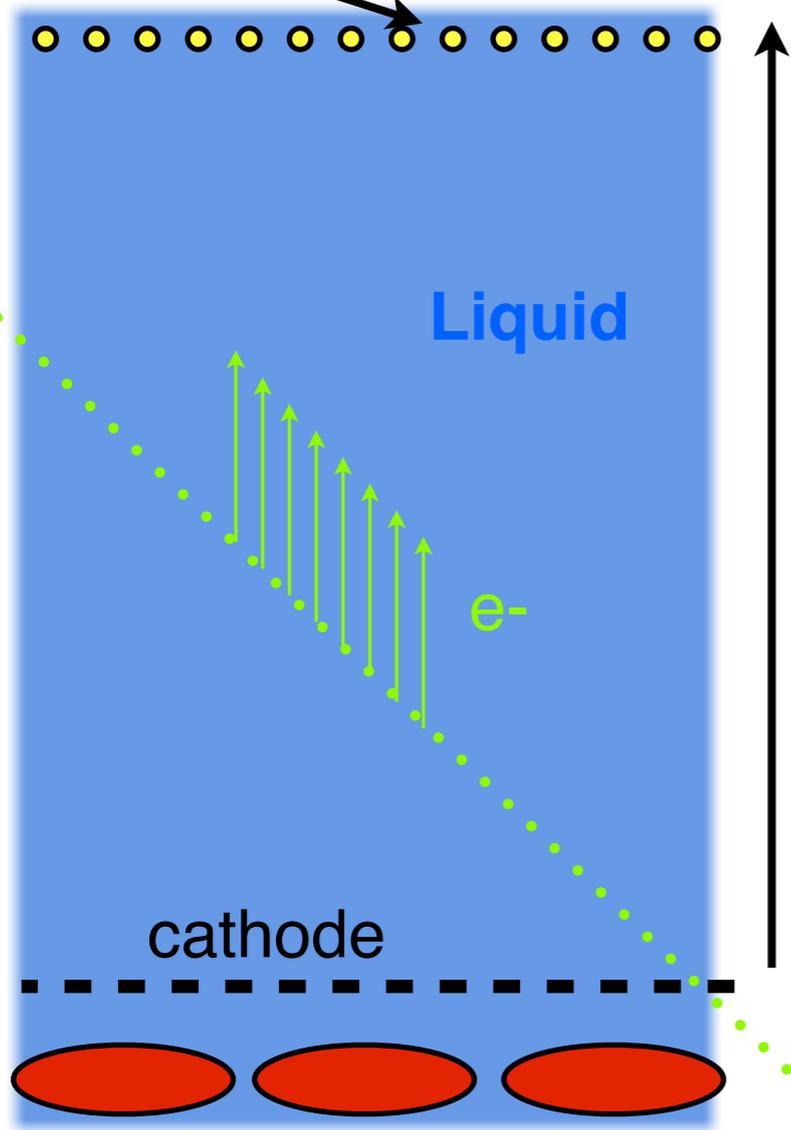
A new massive deep underground neutrino observatory for long baseline neutrino studies, capable of proton decay searches, atmospheric and astrophysical neutrino detection

LAr-TPC single vs double phase

Single phase



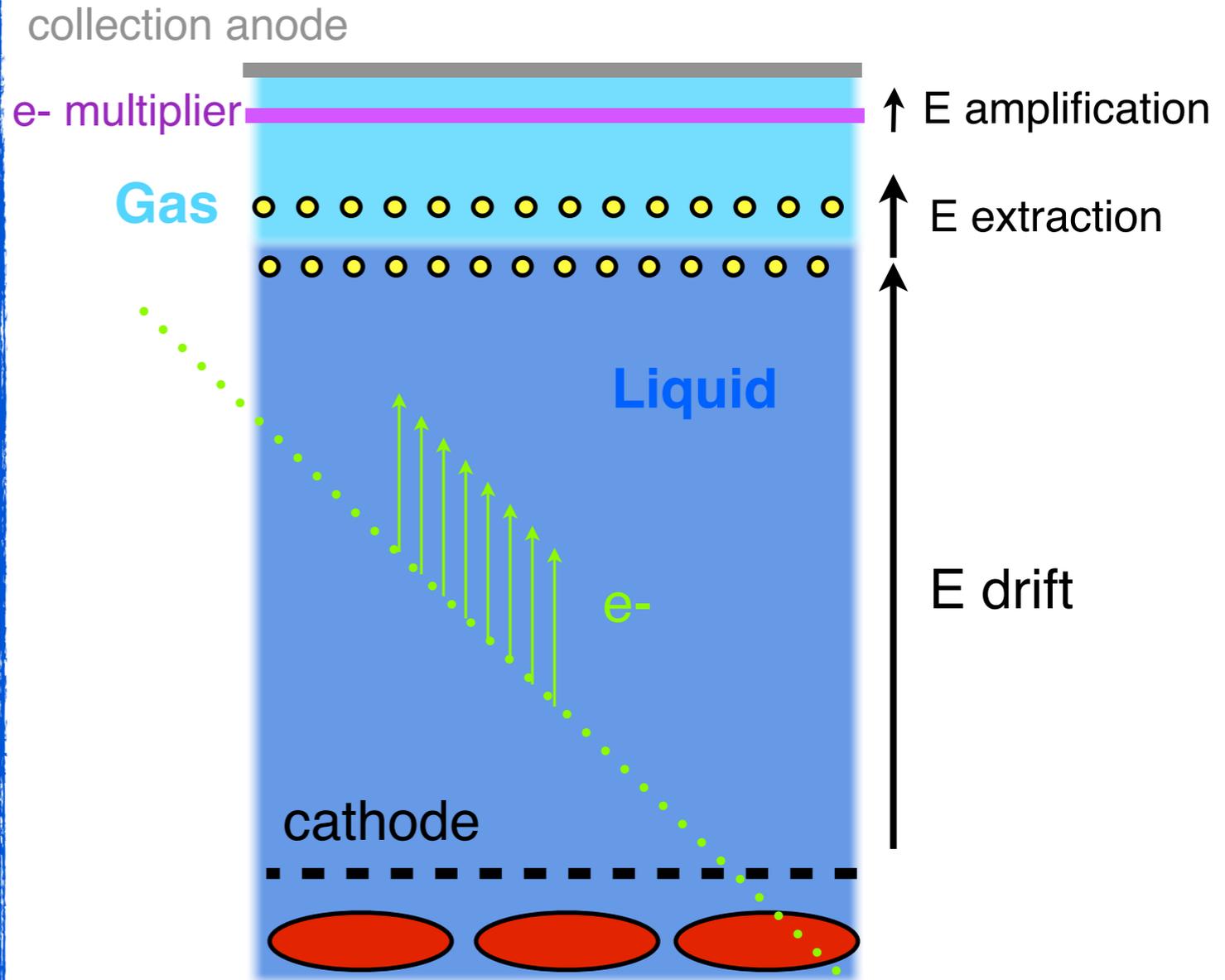
signal readout on wires
x and y coordinate:
2 "views" at 90°
or 3 views at 60°



PMTs (trigger and t_0)

Double phase

signal readout on 2 view collection anode
Signal amplified in the gas



PMTs (trigger and t_0)

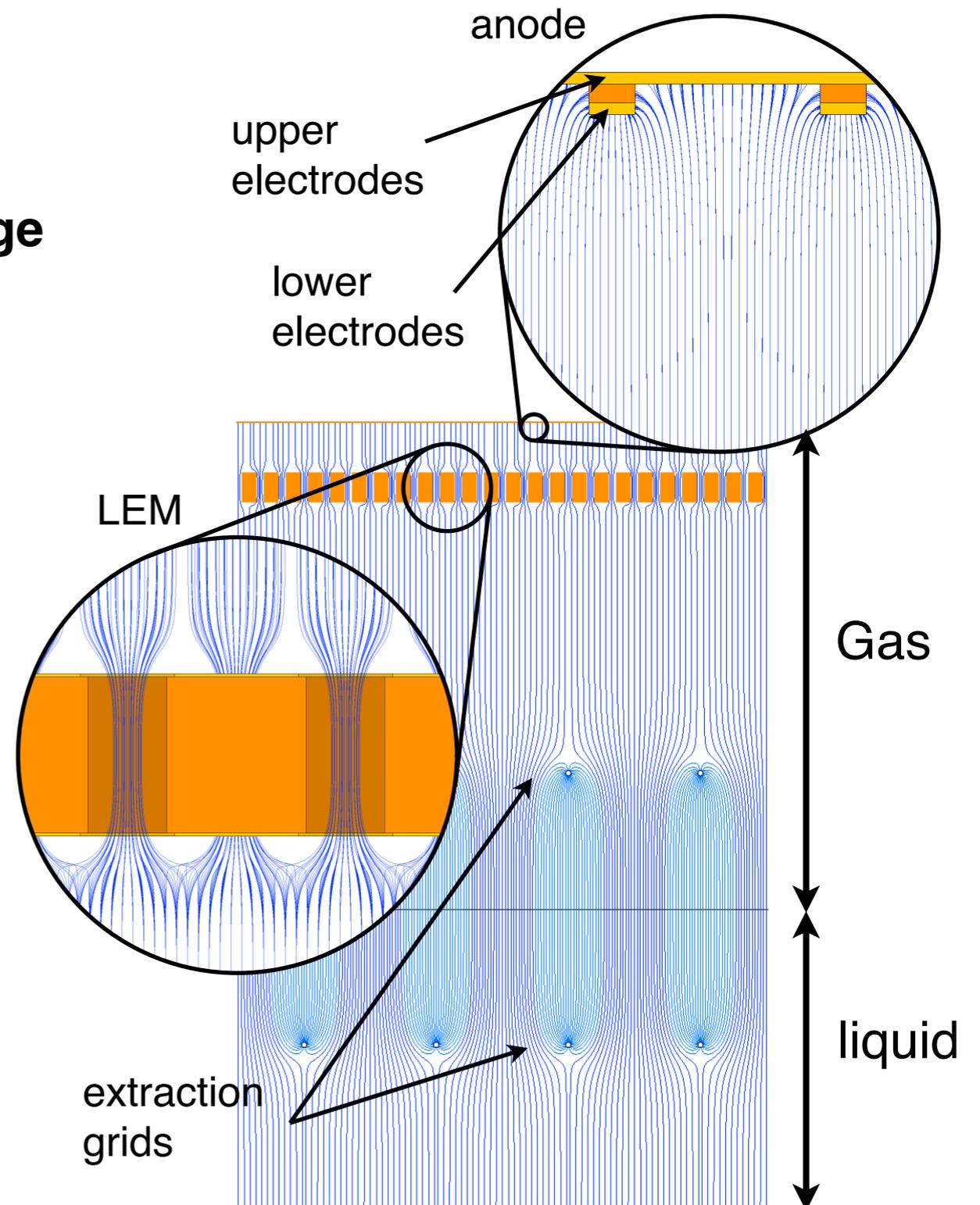
4.) Charge **collection** on a **2D anode readout**
(symmetric unipolar signals with two orthogonal views)

3.) Charge multiplication in the holes of the **Large Electron Multiplier (LEM)**

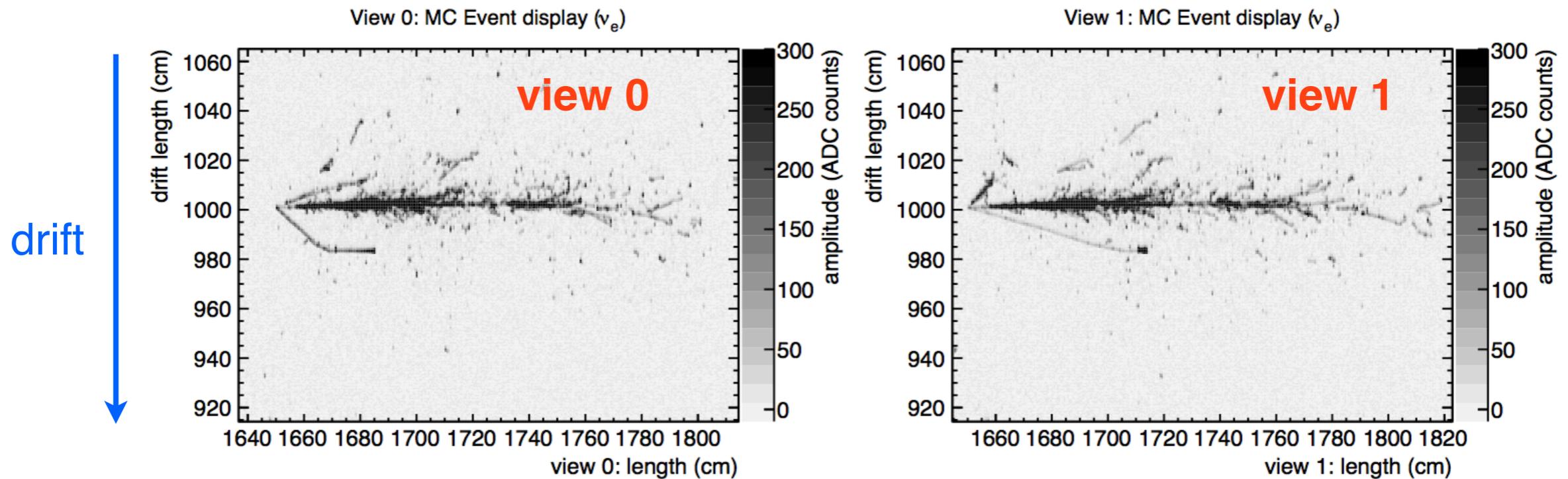


2.) Drift electrons are efficiently emitted into the gas phase

1.) Ionization electrons drift towards the liquid argon surface



ν_e CC event in CLACIER



- ✓ Excellent energy resolution and tracking performance. Efficient background rejection (e.g. $\text{NC}\pi^0$ from $\text{CC}\nu_e$)
- ✓ High granularity: ~ 0.05 cm in drift direction, 3mm in transverse direction
- ✓ Very high signal-to-noise (>100) thanks to amplification in gas. \Rightarrow build large detectors with longer drifts (~ 20 m) and larger readout capacitances.
- ✓ Adjustable Energy threshold \Rightarrow sensitivity from sub-GeV to multi-GeV

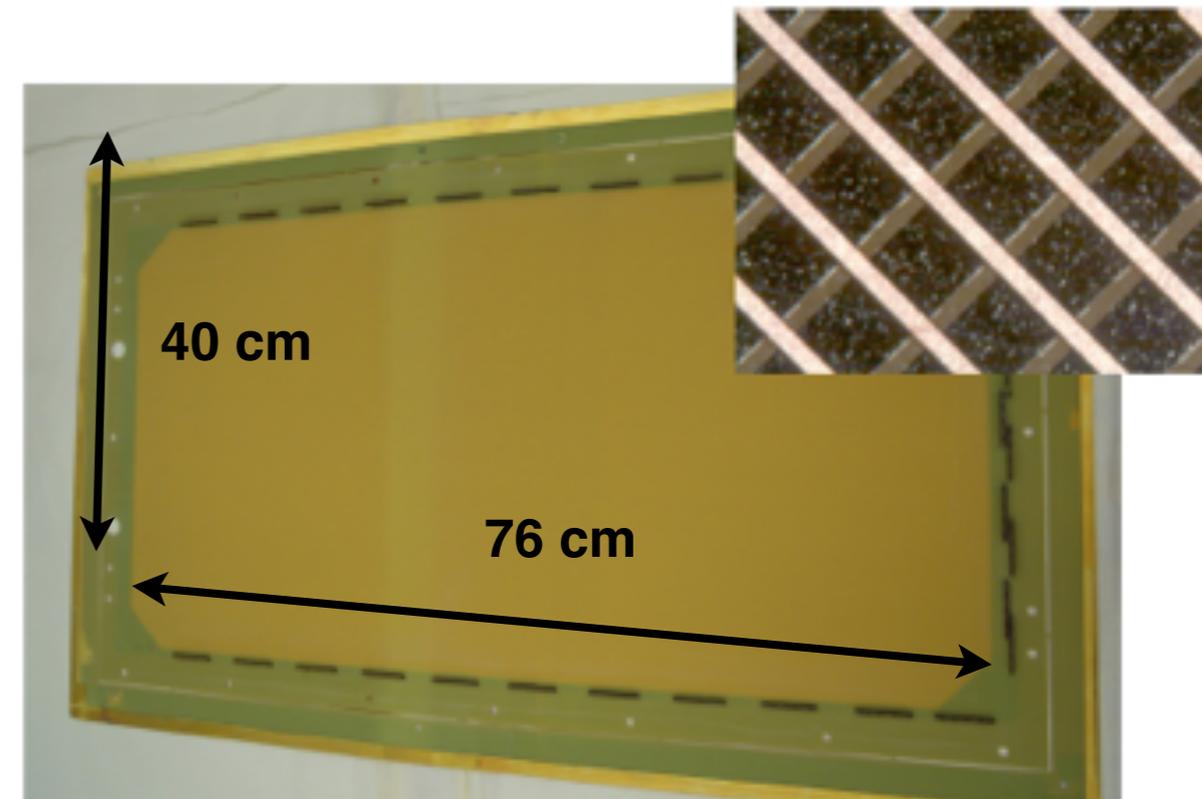
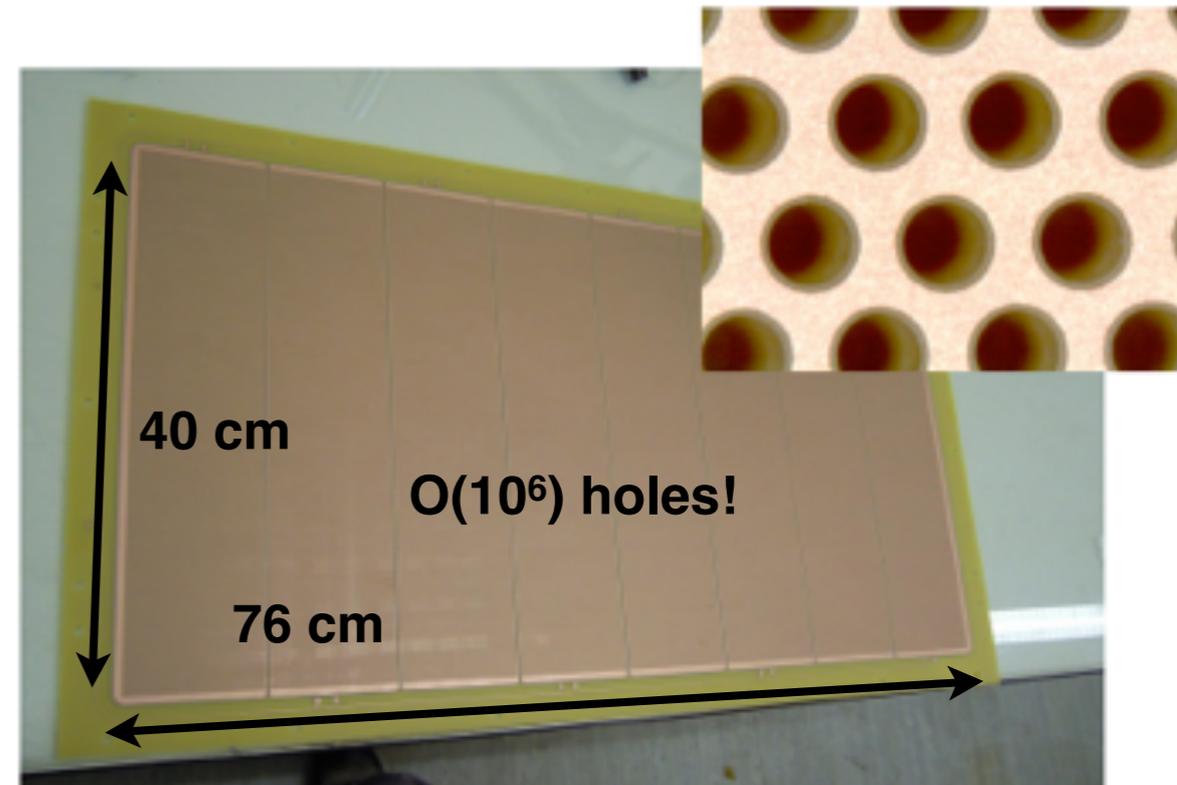
Large Electron Multiplier (LEM)

- * Macroscopic Gas hole multiplier
- * more robust than GEMs (cryogenic temperatures, discharge resistant)
- * manufactured with standard PCB techniques
- * Large area coverable by 50x50 cm² modules
- * Light quenching within the holes

2D projective anode readout

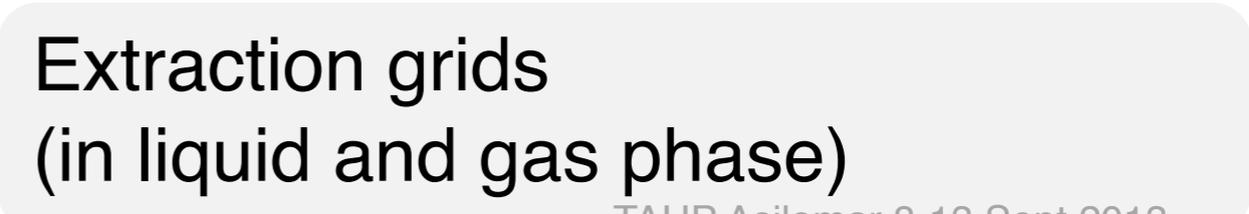
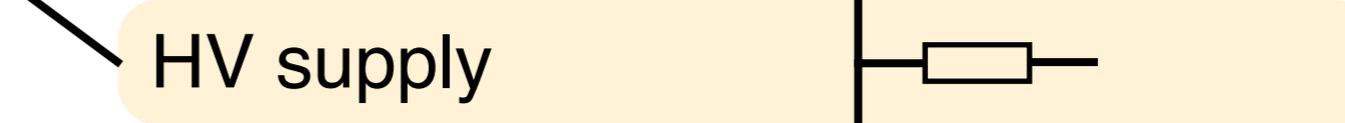
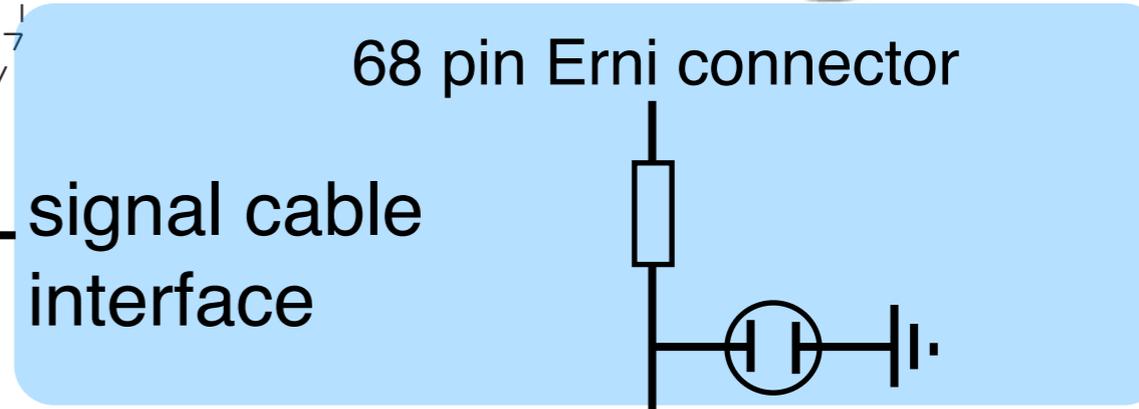
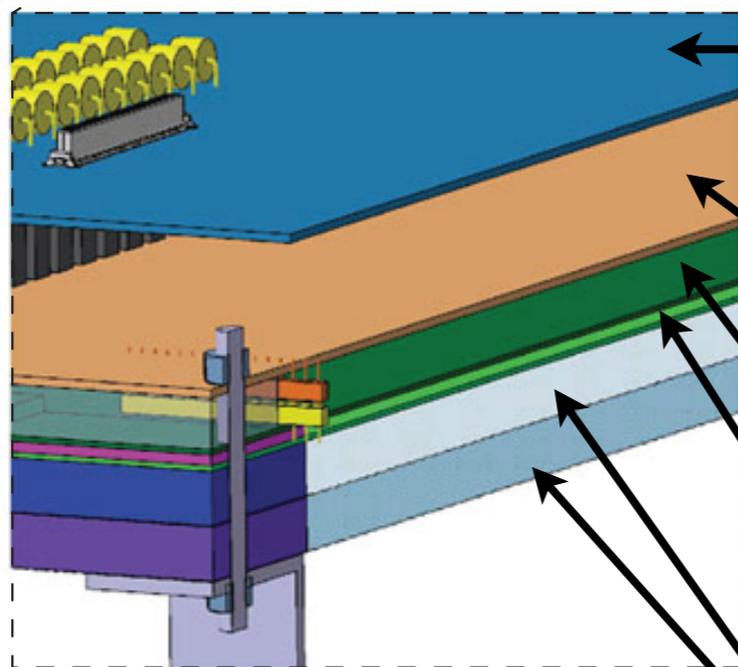
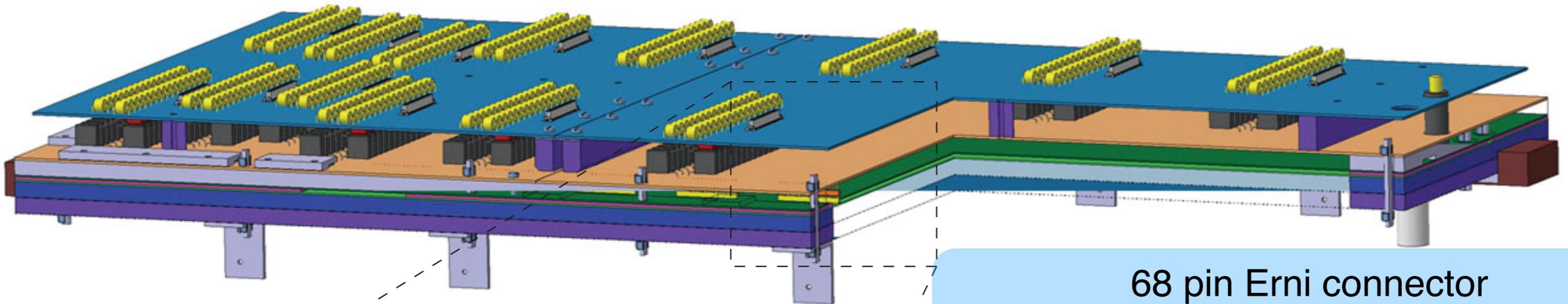
- * Charge equally collected on two sets of strips (views)
- * Readout independent of multiplication
- * Signals have the same shape for both views:
 - two collection views (unipolar signals)
 - no induction view (bipolar signals) as in the case of a LAr-TPC with induction wires

So far largest area LEM/2D anode produced!



Compact Charge Readout Design (CRP)

Single Compact readout module of square meter doing extraction, amplification and readout



68 pin Erni connector
signal cable interface

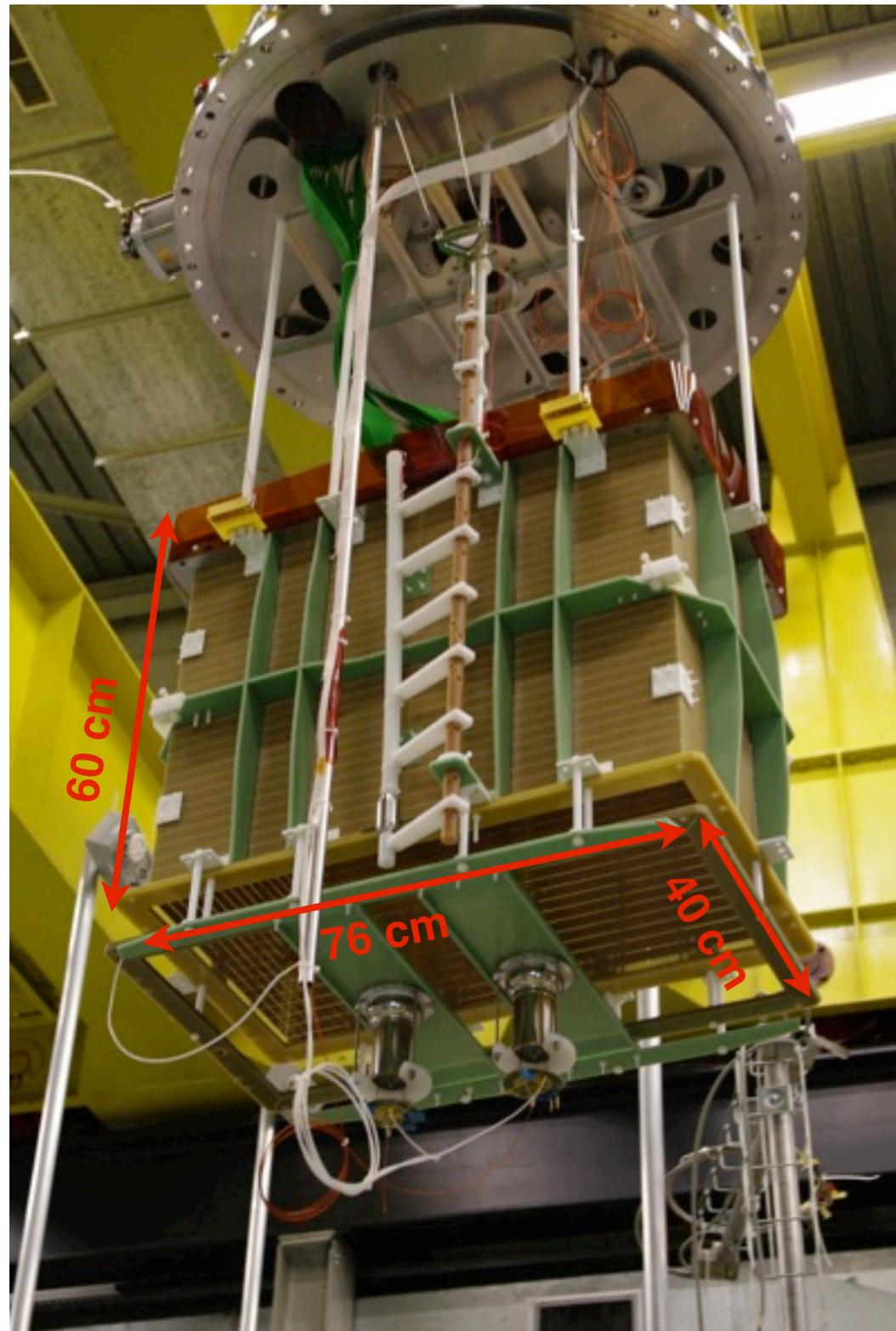
HV supply

2D anode readout

Large Electron Multiplier (LEM)

Extraction grids
(in liquid and gas phase)

detector fully assembled



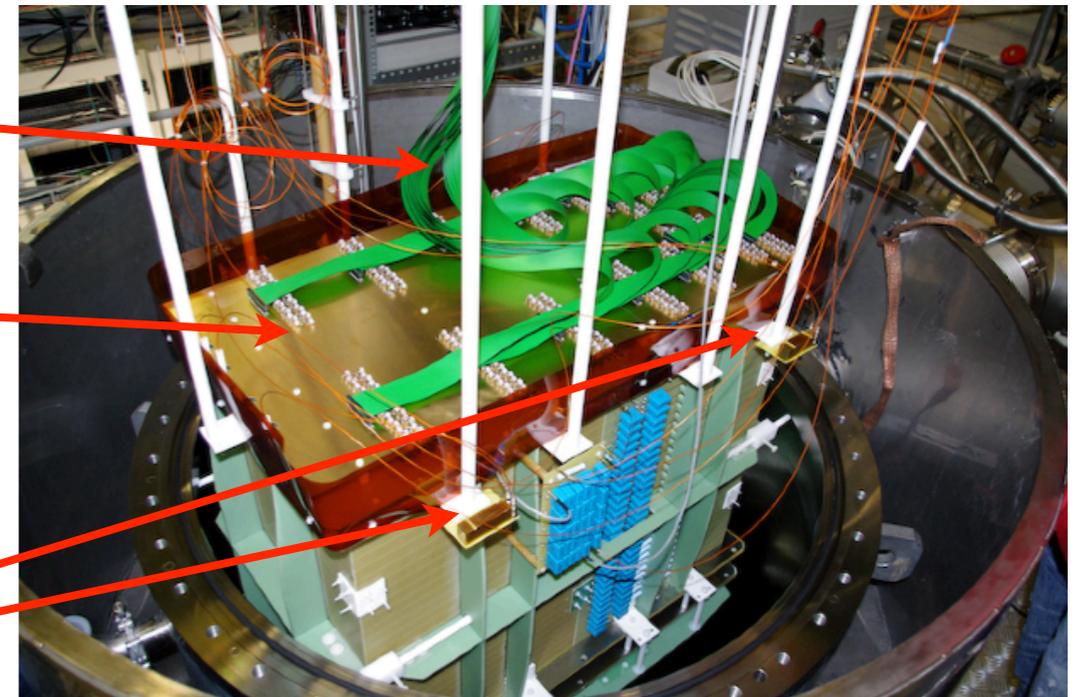
A. Badertscher et al. [JINST 8 \(2013\)P04012](#),

going into the ArDM cryostat

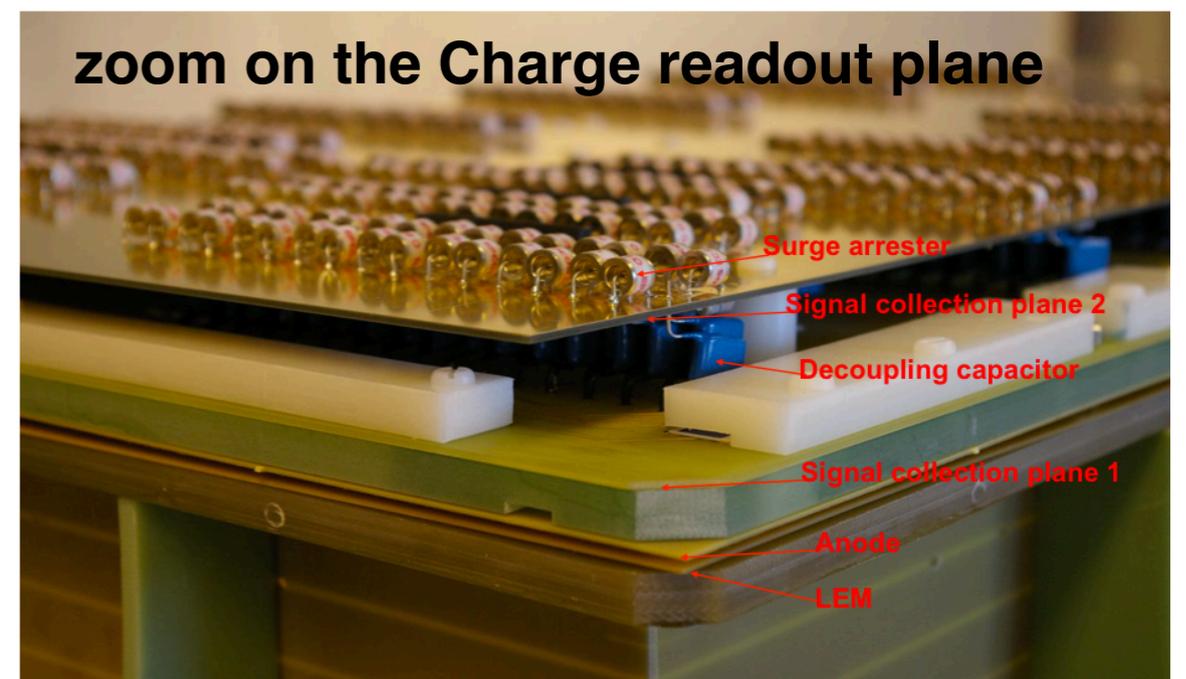
16 signal cables

charge readout plane

4 capacitive level meters

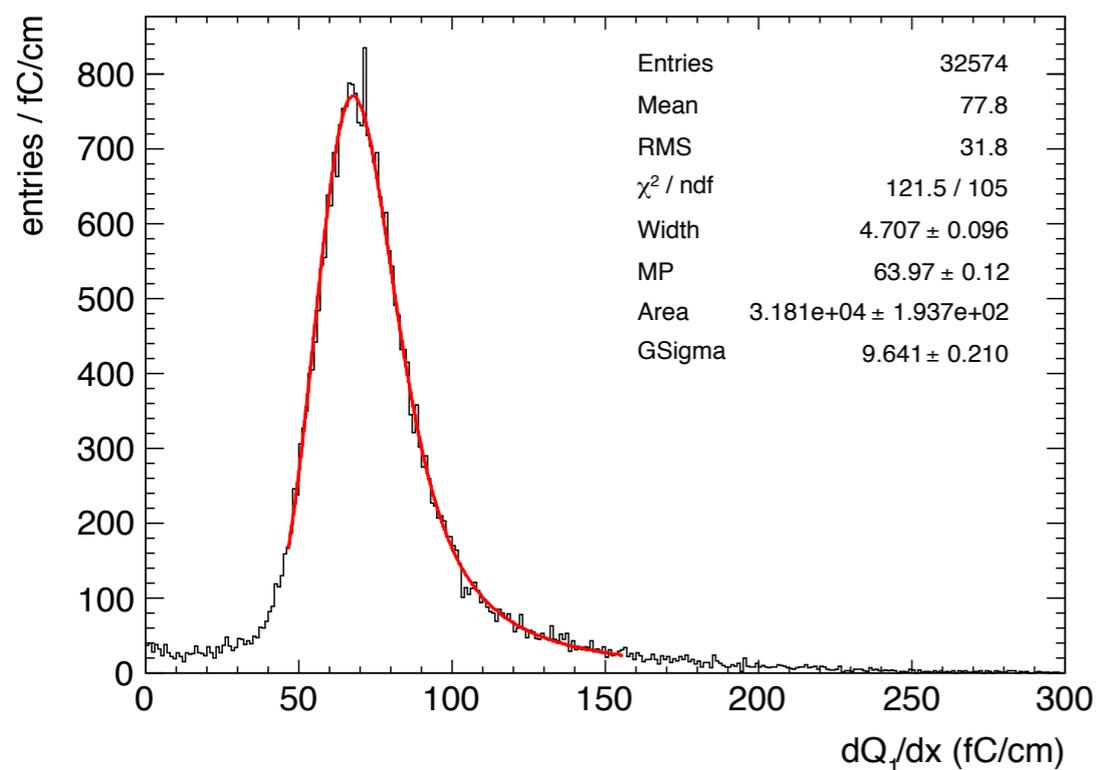
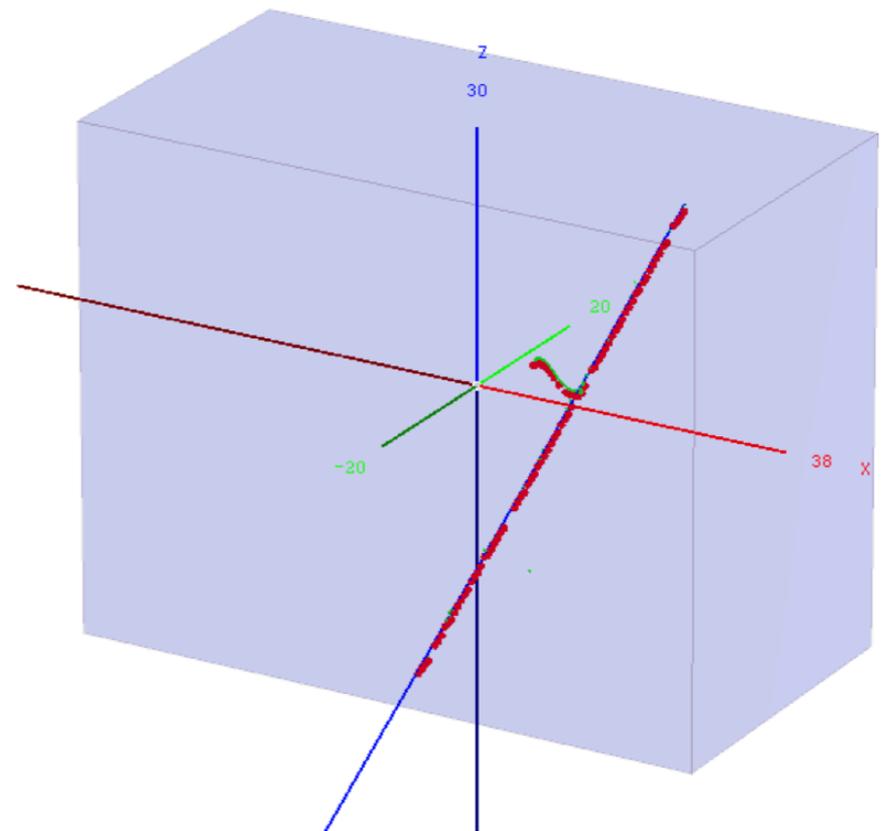
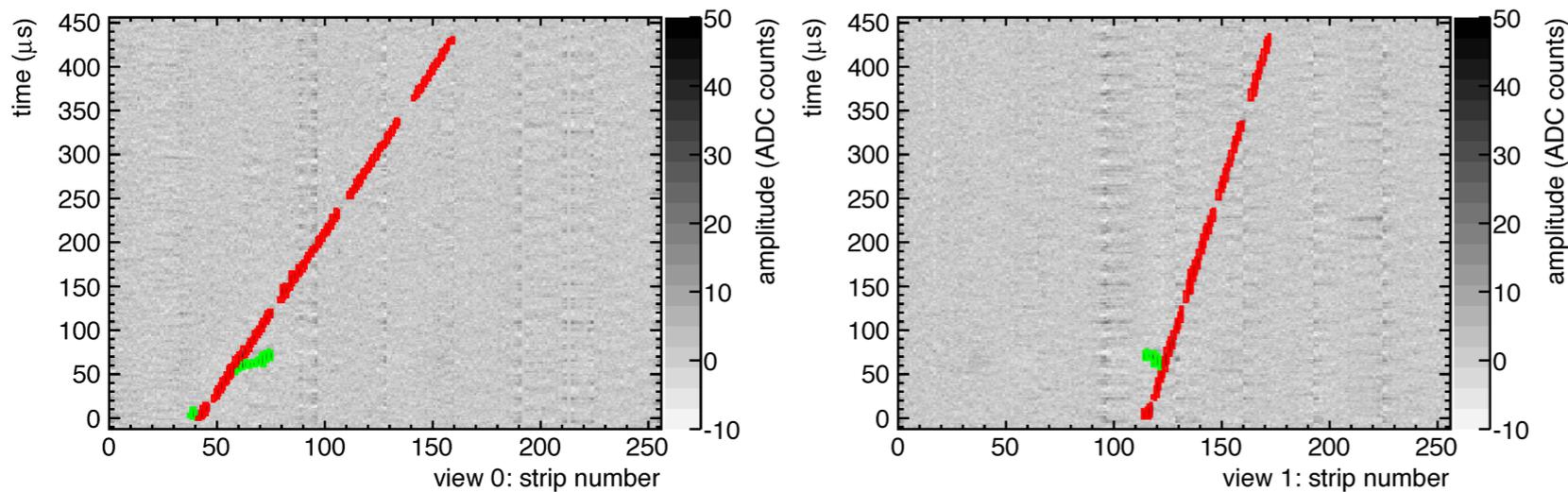


zoom on the Charge readout plane



We have operated the detector for the first time in October 2011 during more than 1 month.
 Operated under controlled pressure: 1023±1 mbar [A. Badertscher et al. JINST 8 \(2013\)P04012](#),

delta ray identified and reconstructed in 3D!



Effective gain:

$$(dQ/dx_{\text{view0}} + dQ/dx_{\text{view1}}) / dQ/dx_{\text{MIP}} (\approx 10 \text{ fC/cm})$$

$$\langle dQ/dx \rangle = 146 \text{ fC/cm}$$

➡ effective gain ≈ 14.6 , (S/N ≈ 30)

charge sharing between the two collection views:

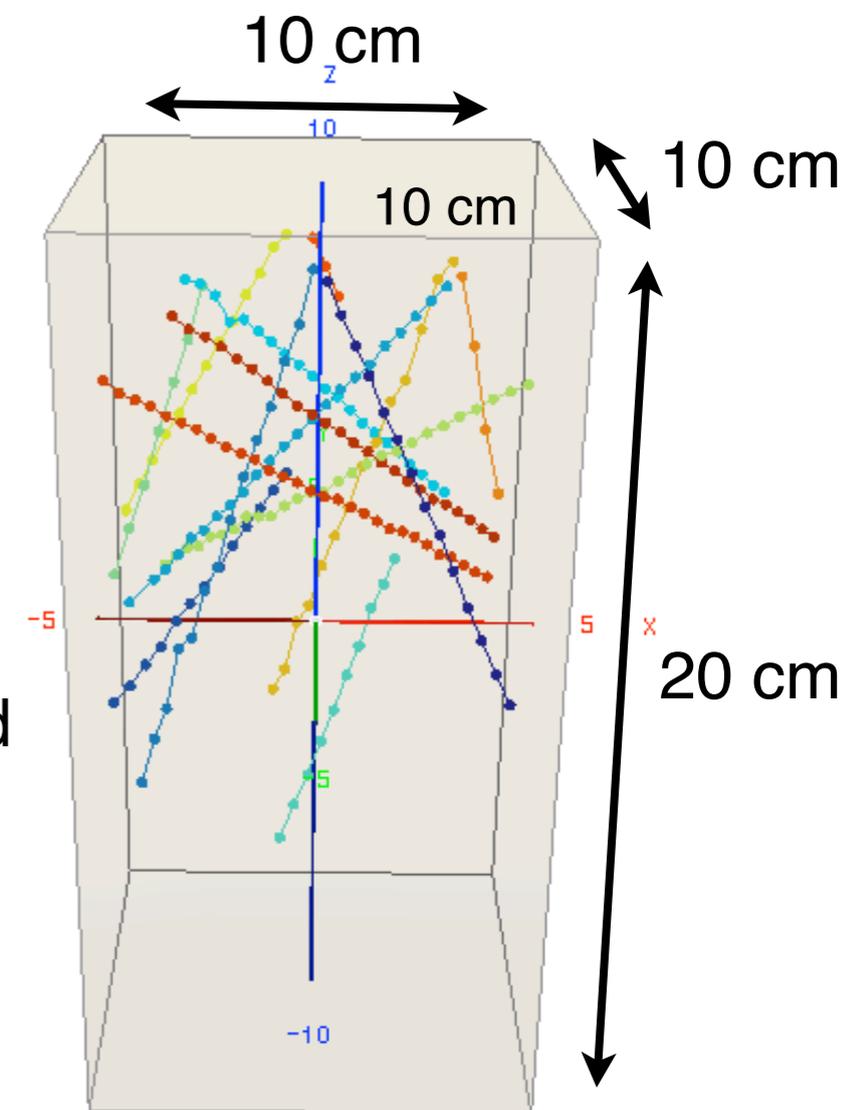
$$(Q_1 - Q_0) / (Q_1 + Q_0) \approx 8\%$$



With this small chamber, we can collect in a short amount of time a high quality and **large data-sets of cosmic muon**

Some of the things we tested:

- * **Uniformity** of the charge sharing between both views
- * **Stability** of the gain and signal-to-noise-ratio for extended running periods.
- * **Discharges** across the LEM (how frequent? do they affect the gain?..)
- * How can we further **Simplify** the readout?



3D reconstructed muons

Towards large area readout - anode considerations

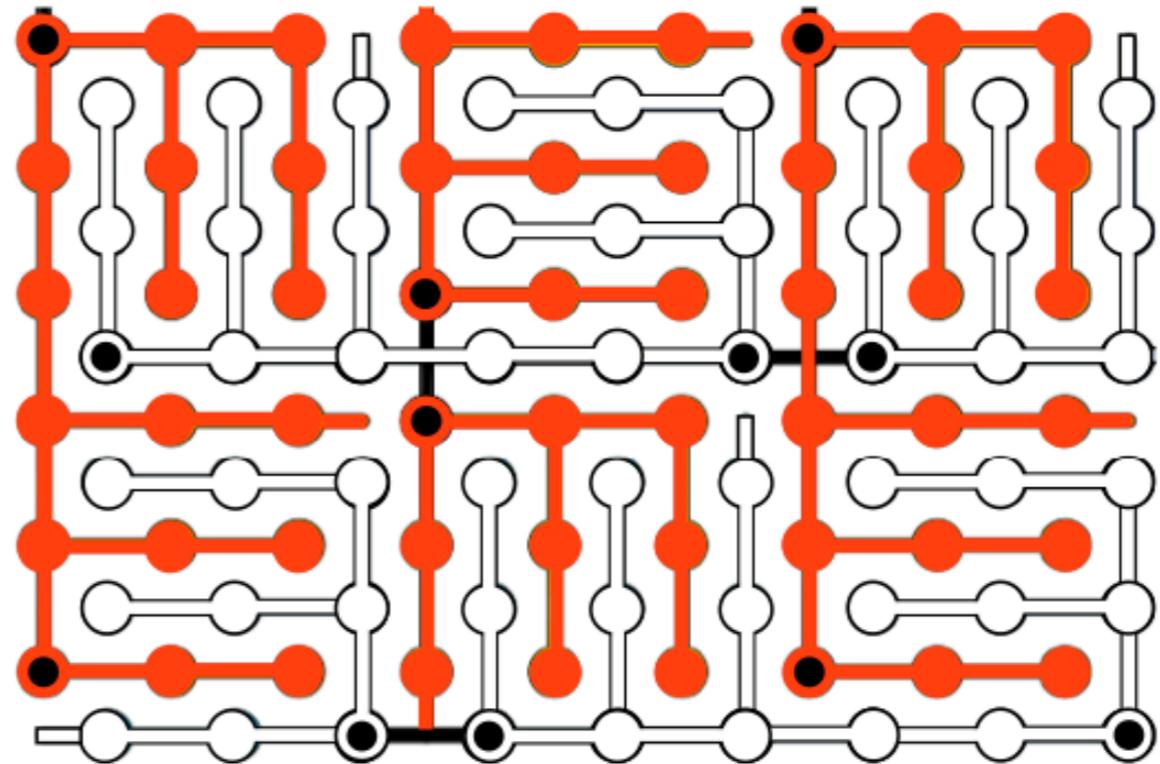
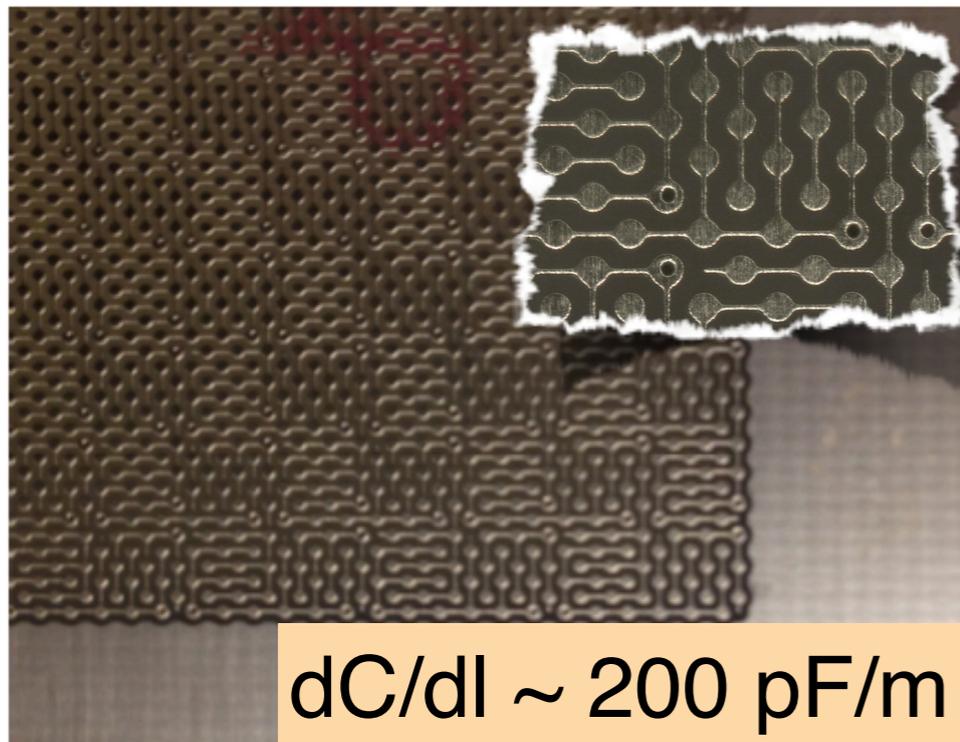
Goal: readout of at least 0.5x0.5 m²

need low capacitance readouts to go large dimensions

previous Kapton type anode dC/dl ~600 pF/m

the anode should:

- i) be easy to manufacture on large scale
- ii) have low capacitance to have long readout strips while keeping the noise to minimum.
- iii) have equal charge sharing between both views



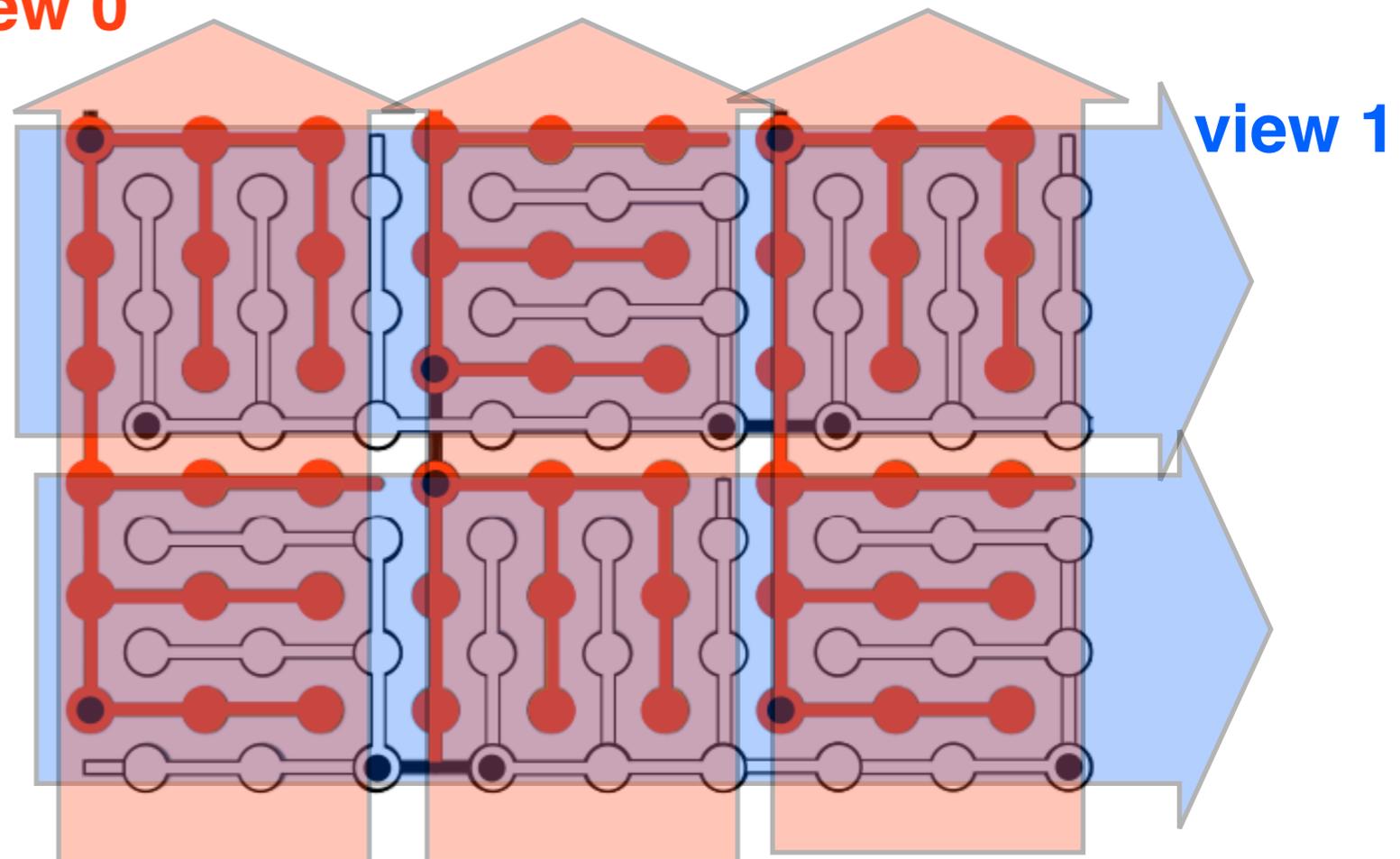
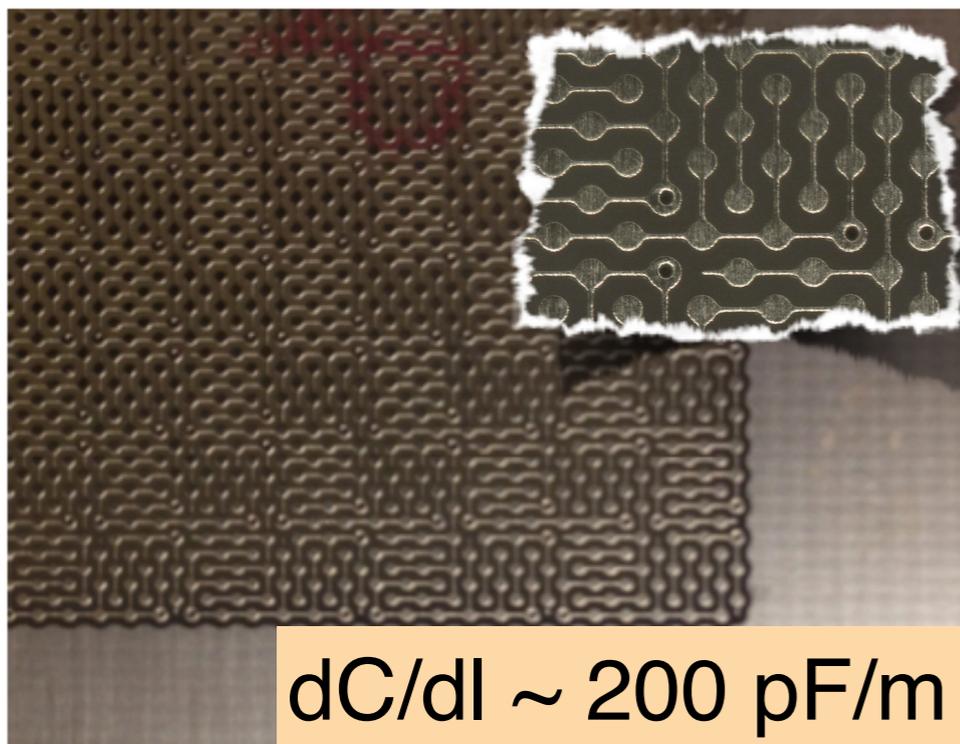
Multi-layer PCB anode designed to be completely x-y symmetric.

Goal: readout of at least 0.5x0.5 m²

the anode should:

- i) be easy to manufacture on large scale
- ii) have low capacitance to have long readout strips while keeping the noise to minimum.
- iii) have equal charge sharing between both views

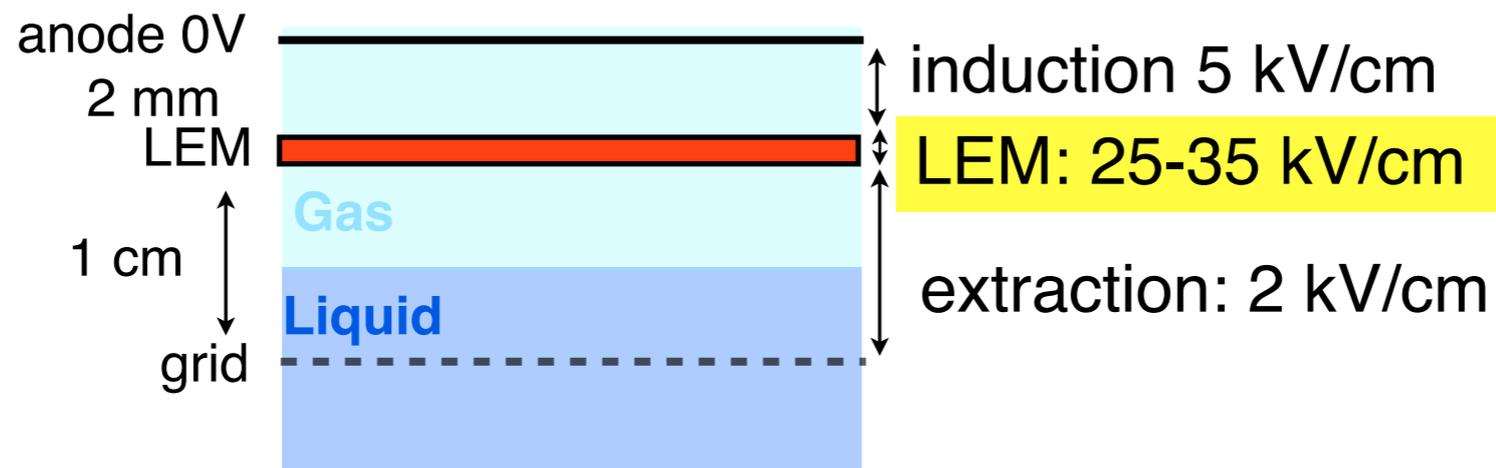
view 0



previous Kapton type anode $dC/dl \sim 600 \text{ pF/m}$

Multi-layer PCB anode designed to be completely x-y symmetric.

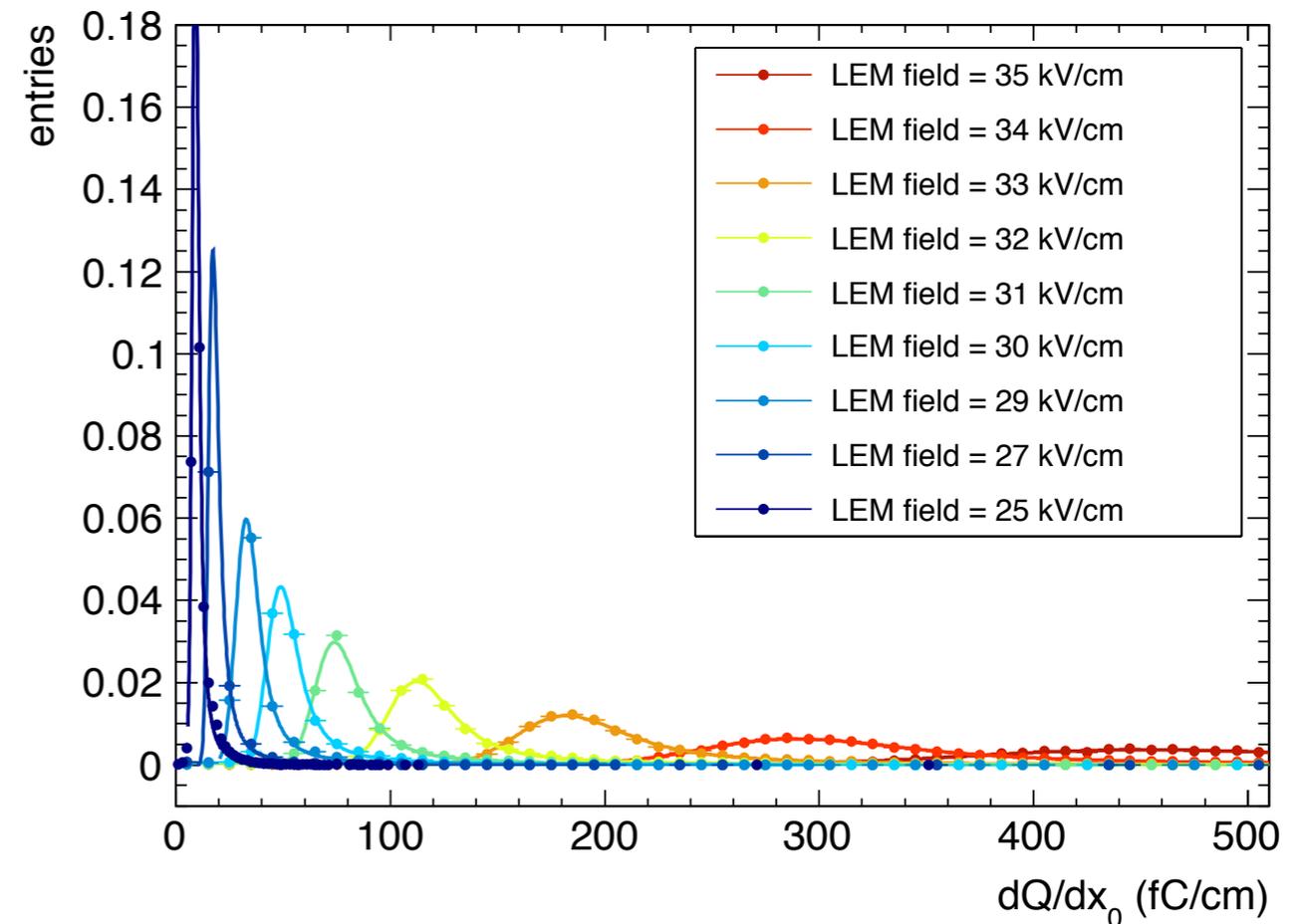
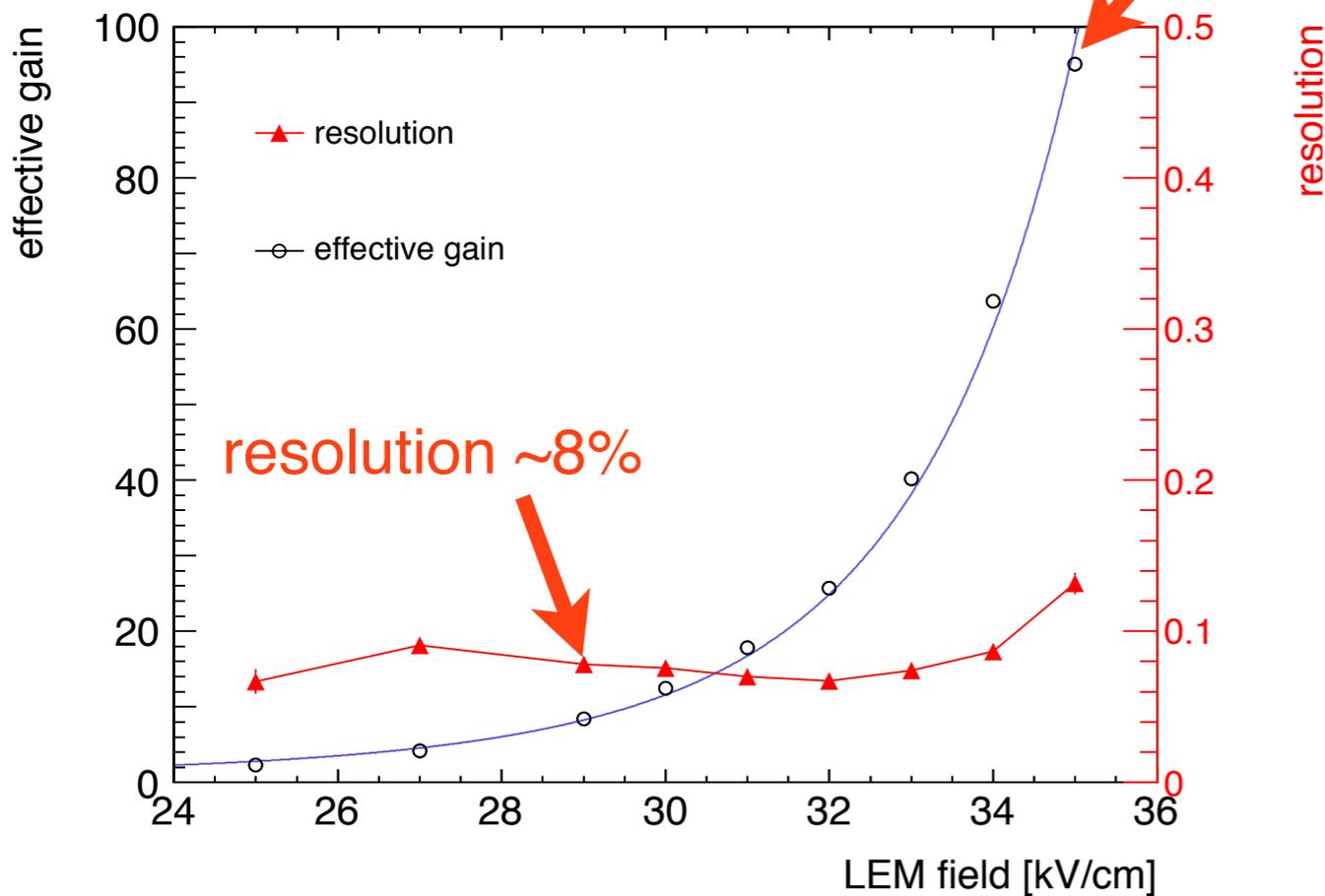
LEM field scan up to gain 90!



onset of discharges @ gain > 90!

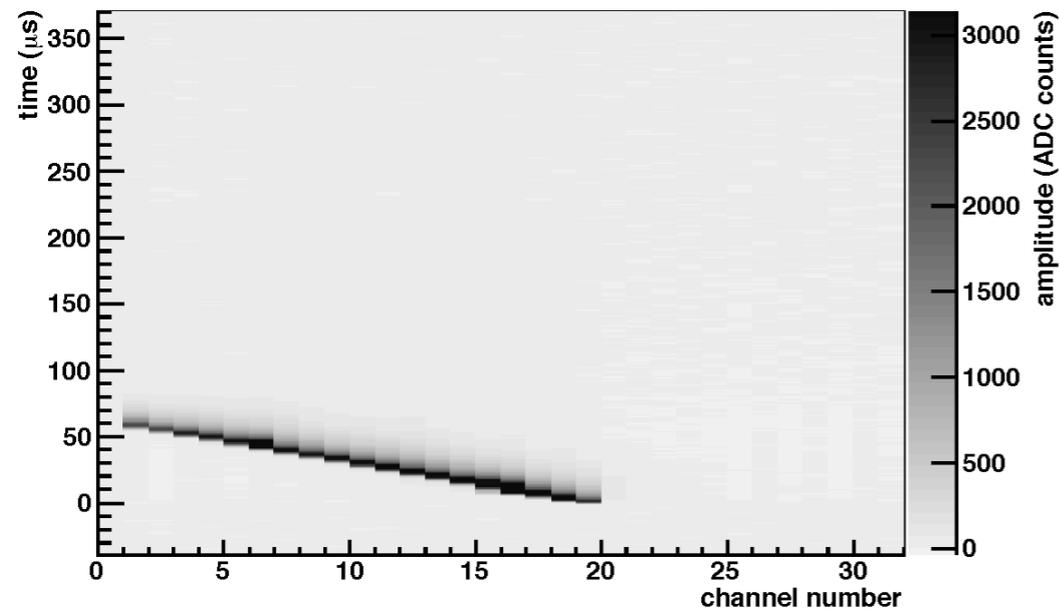
gain and resolution for diff. LEM fields

Landau distributions for diff. LEM fields

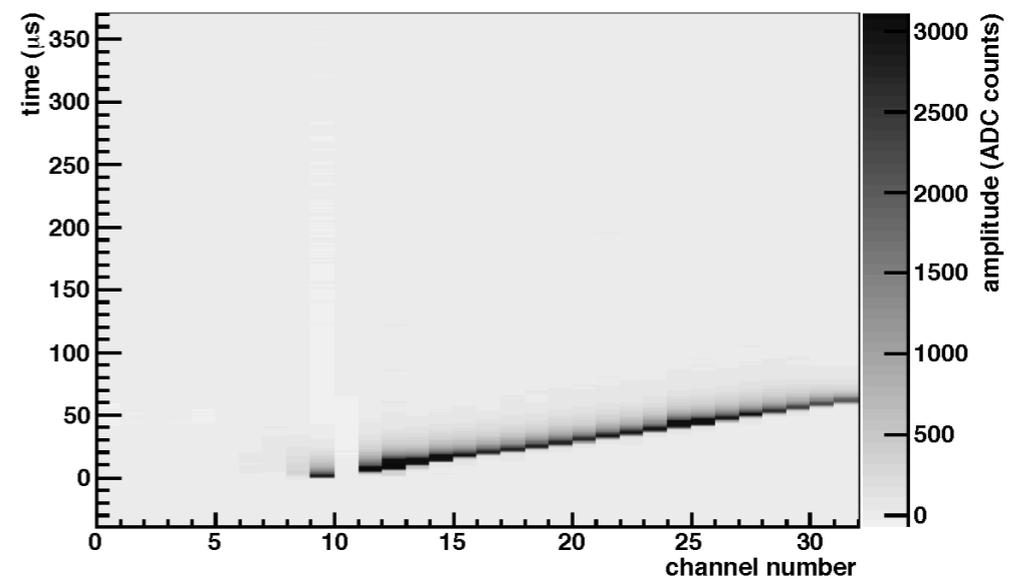


LEM: 35 kV/cm, induction: 5 kV/cm, extraction: 2 kV/cm, drift: 0.5 kV/cm

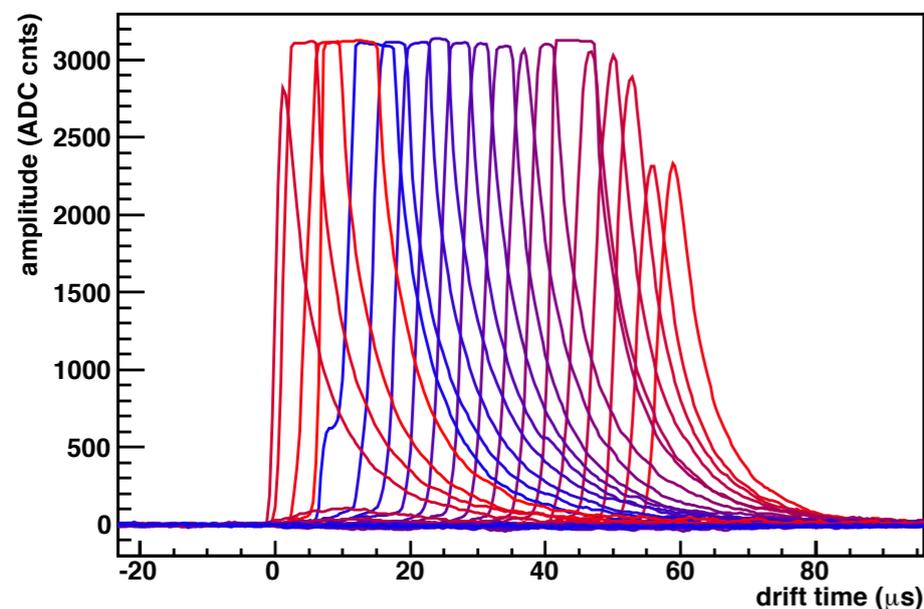
View 0: Event display (run 15949, event 21)



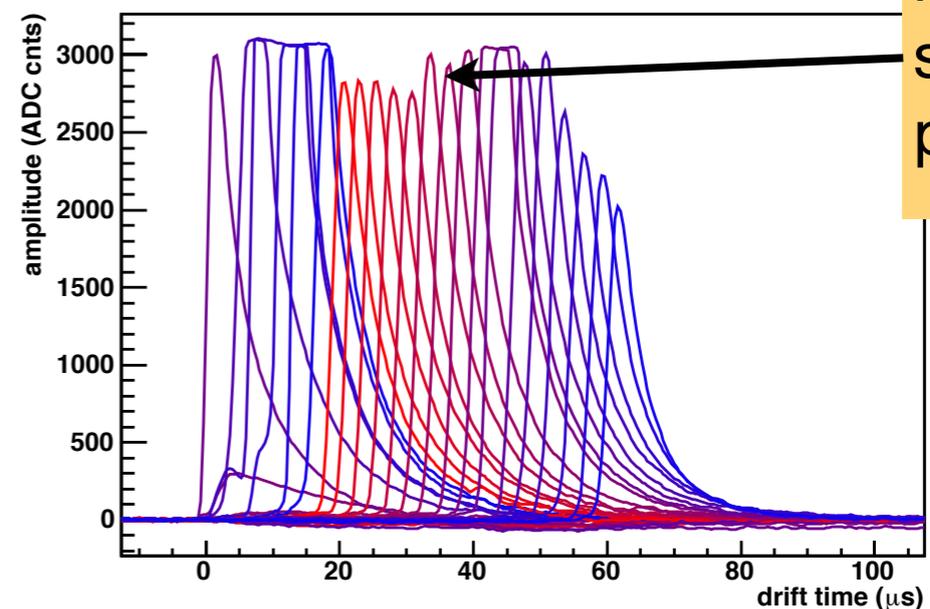
View 1: Event display (run 15949, event 21)



View 0: Signals (run 15949, event 21)



View 1: Signals (run 15949, event 21)



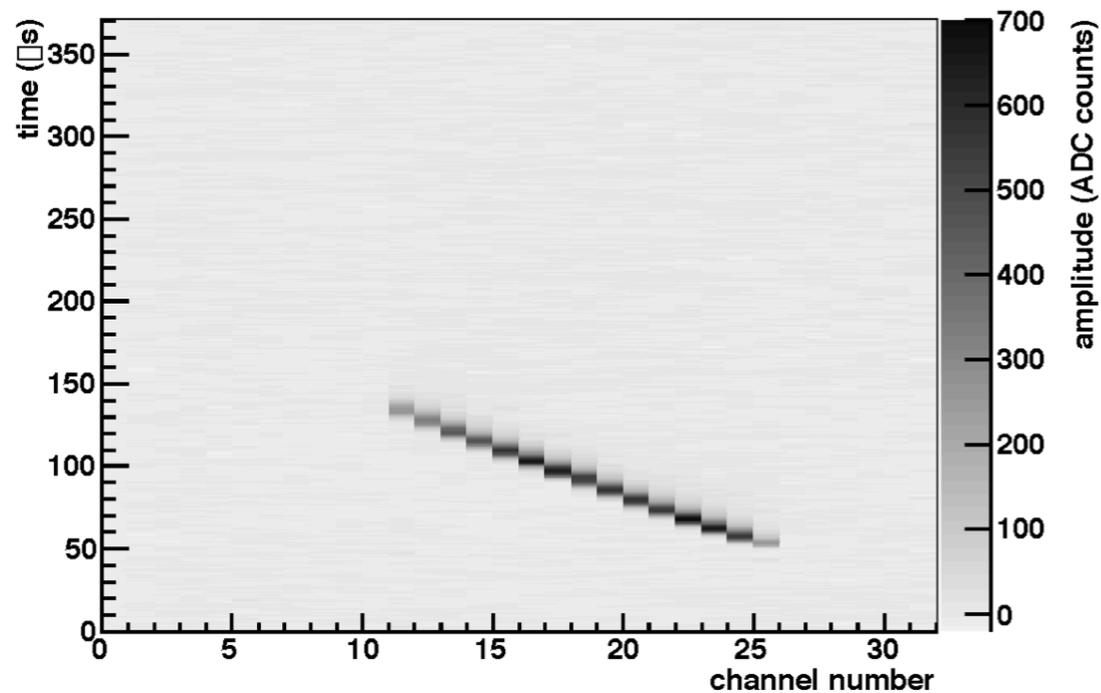
mip signals saturate preamplifier!

In future versions dynamic range of the preamp will be adapted to the gain.
non-linear behaviour to adapt to a wide dynamic range

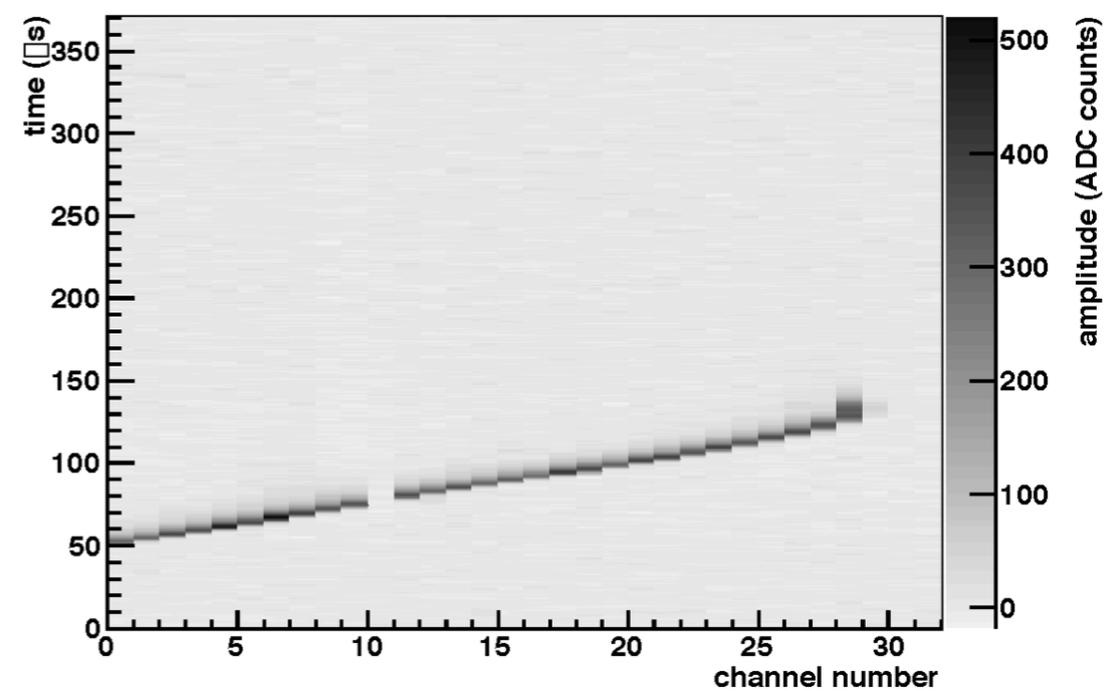
Event at effective gain ~ 20

LEM: 31 kV/cm, induction: 5 kV/cm, extraction: 2 kV/cm, drift: 0.5 kV/cm

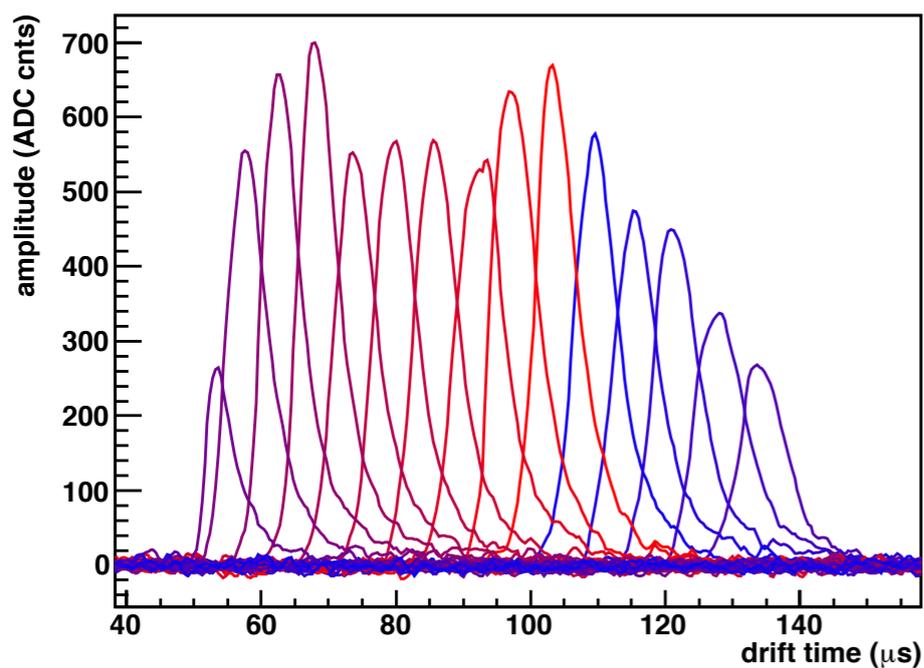
View 0: Event display (run 15937, event 22)



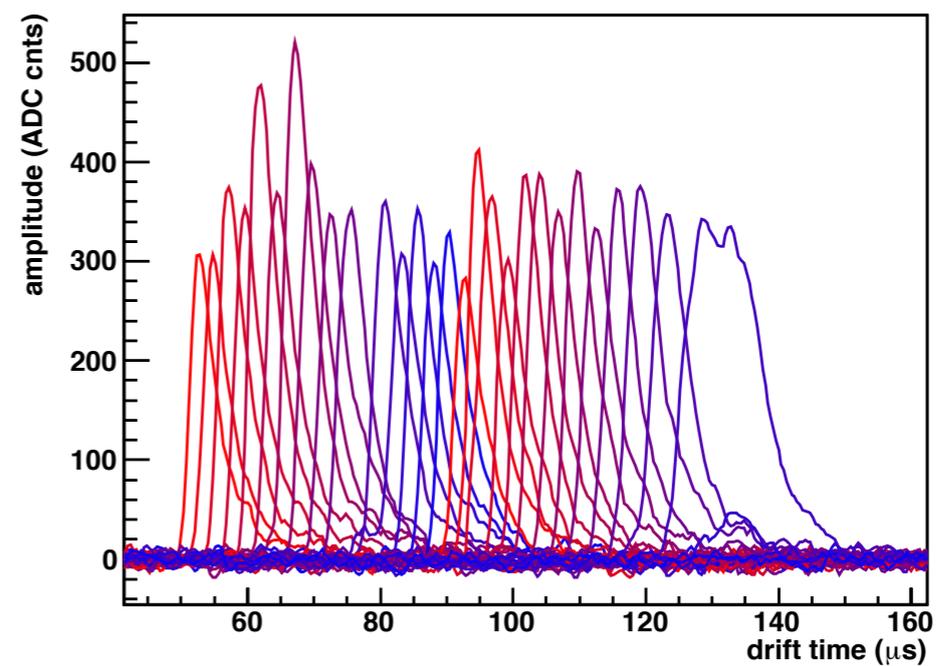
View 1: Event display (run 15937, event 22)



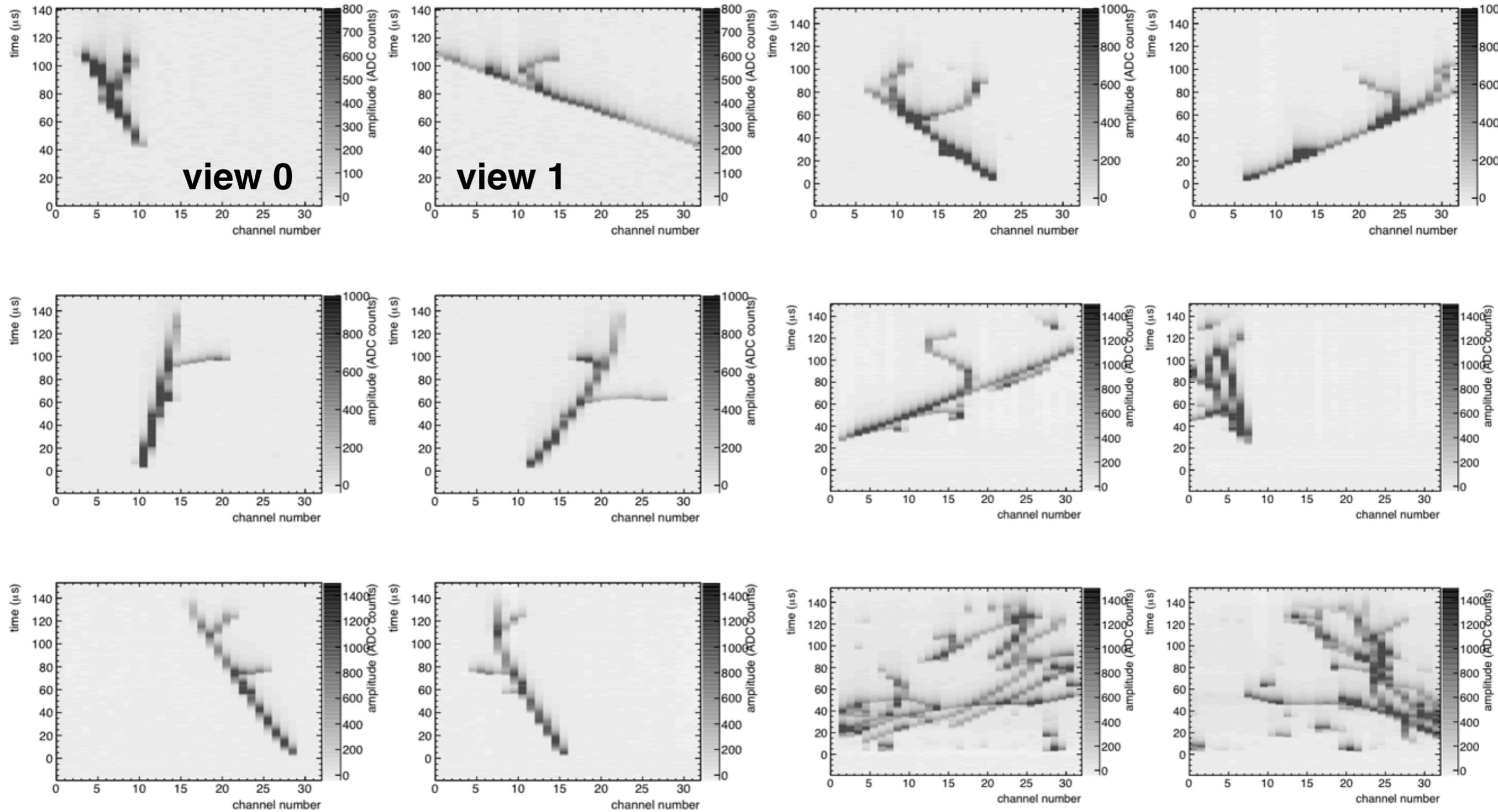
View 0: Signals (run 15937, event 22)



View 1: Signals (run 15937, event 22)



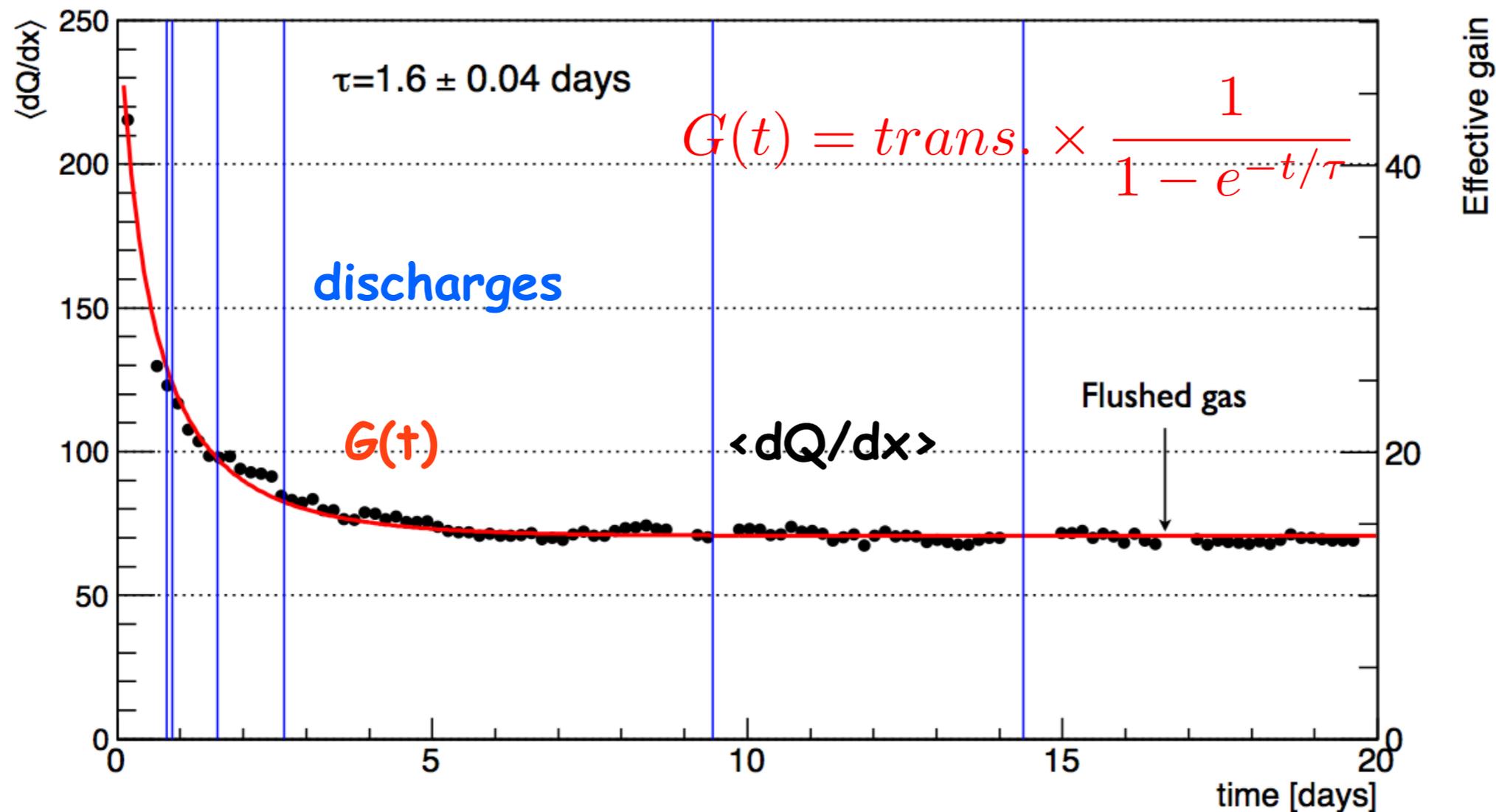
gain ~ 30



Evolution of $\langle dQ/dx \rangle$ corrected for variations of the pressure

* Gain is stable over a period of ~ 15 days once the LEM has charged up (w/ time constant $\tau \sim 1.5$ days)

* The discharges do not lead to a change of overall gain

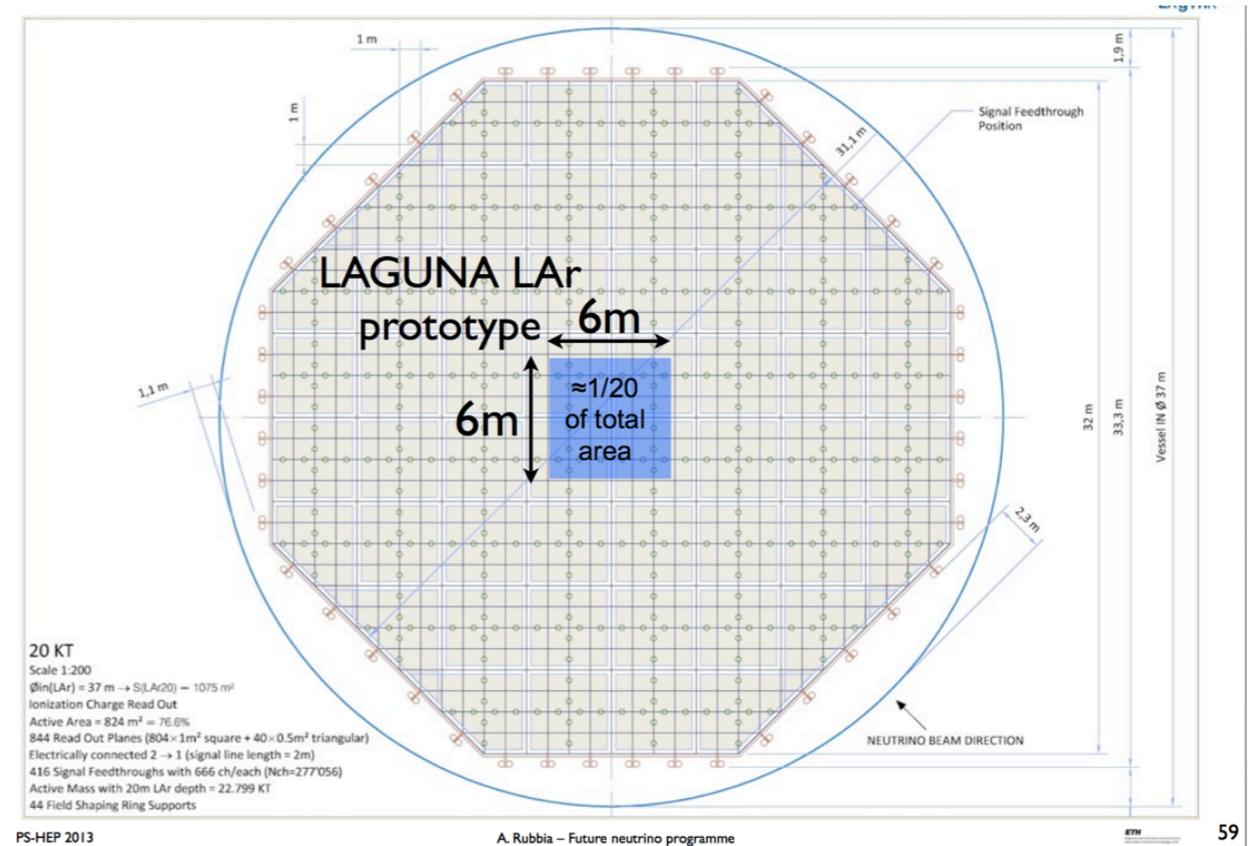
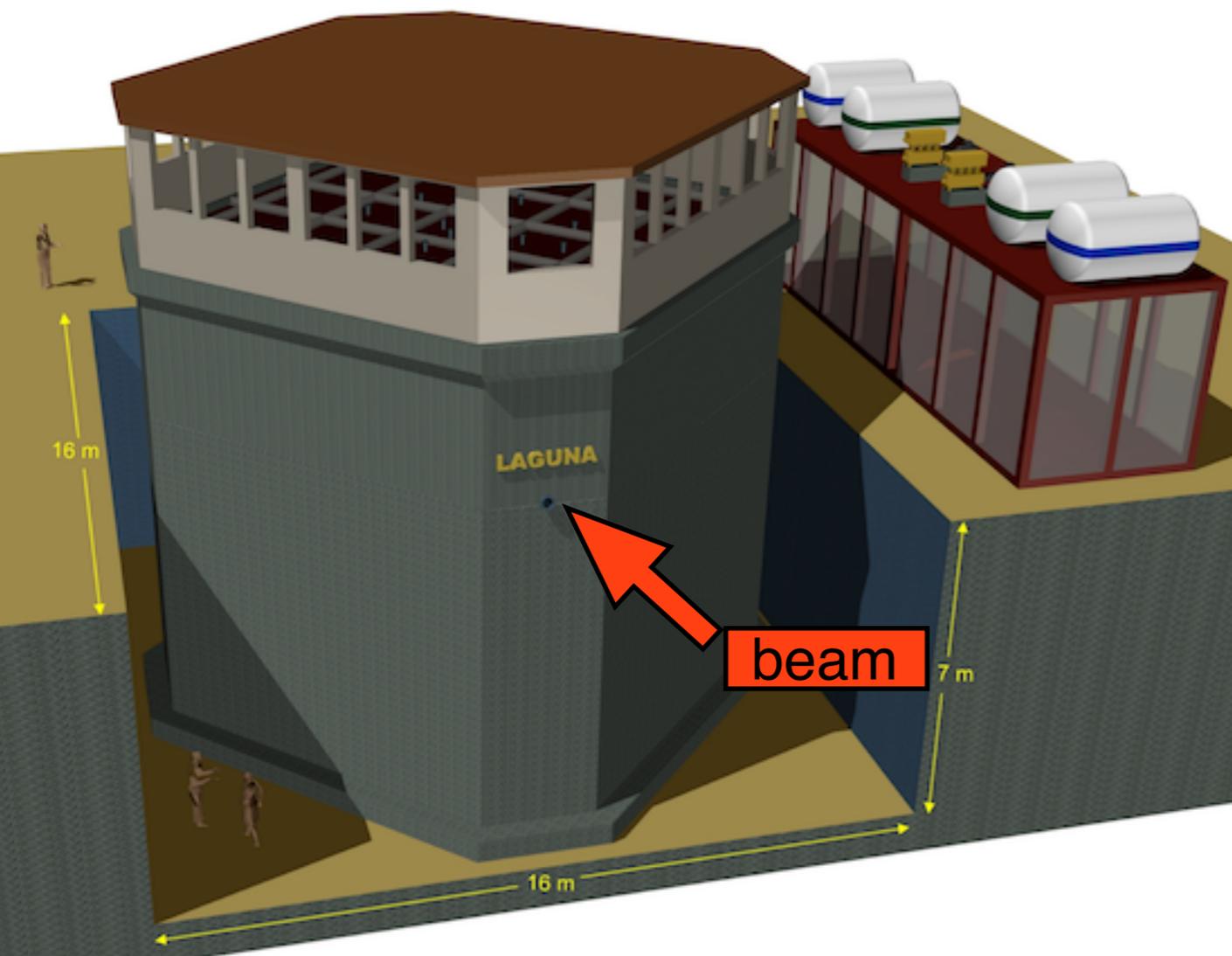


~ 15 days operation under stable gain of ~ 15

Next milestone: 6x6x6m³ prototype

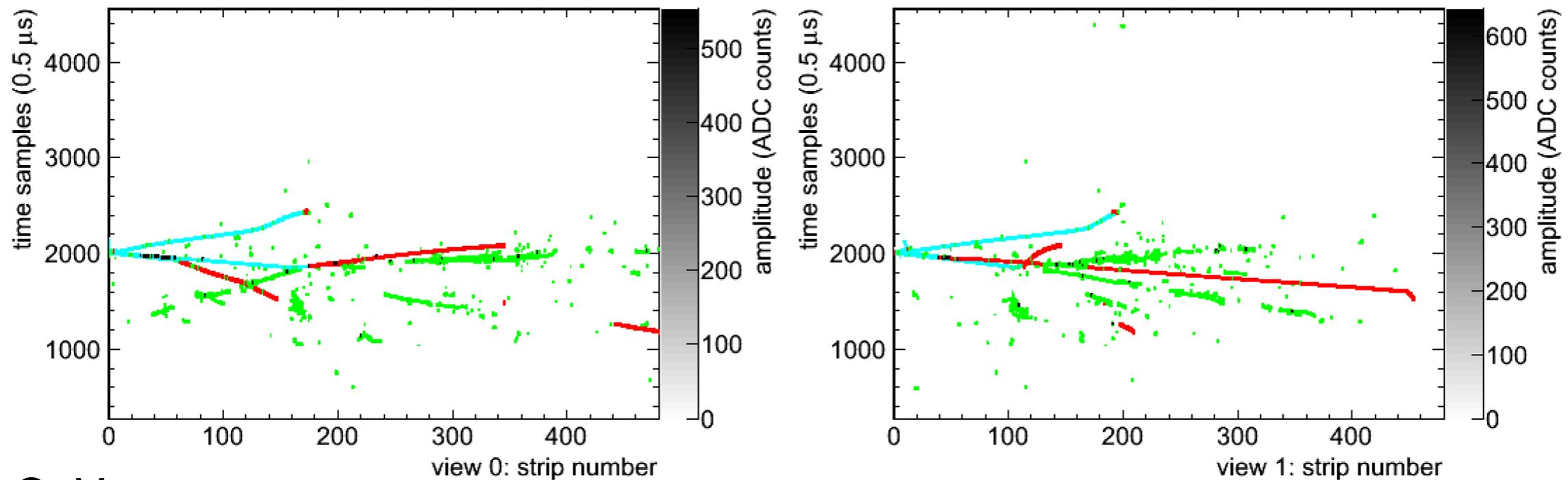
Next milestone: Large-scale LBNO detectors prototyping at CERN, with priority emphasis on a large double-phase LAr demonstrator, using charged-particle test beams (2014-2017). TDR submitted to SPS Committee in June.

6x6x6m³ compared to GLACIER 20 kt

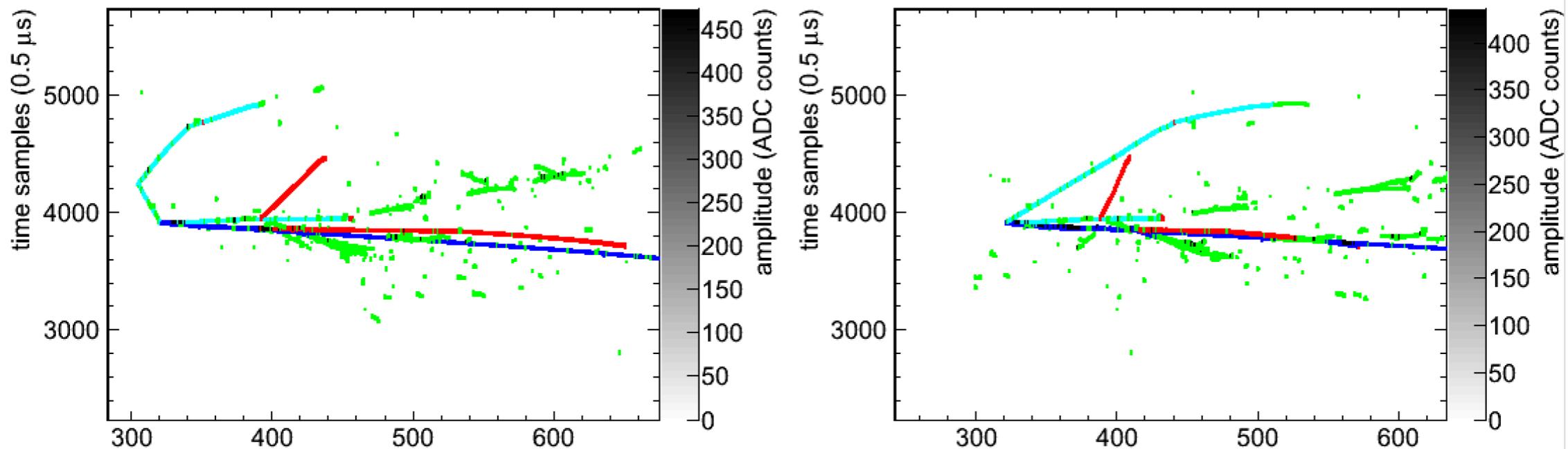


5 GeV pi-

pions, electrons/positrons, protons, muons



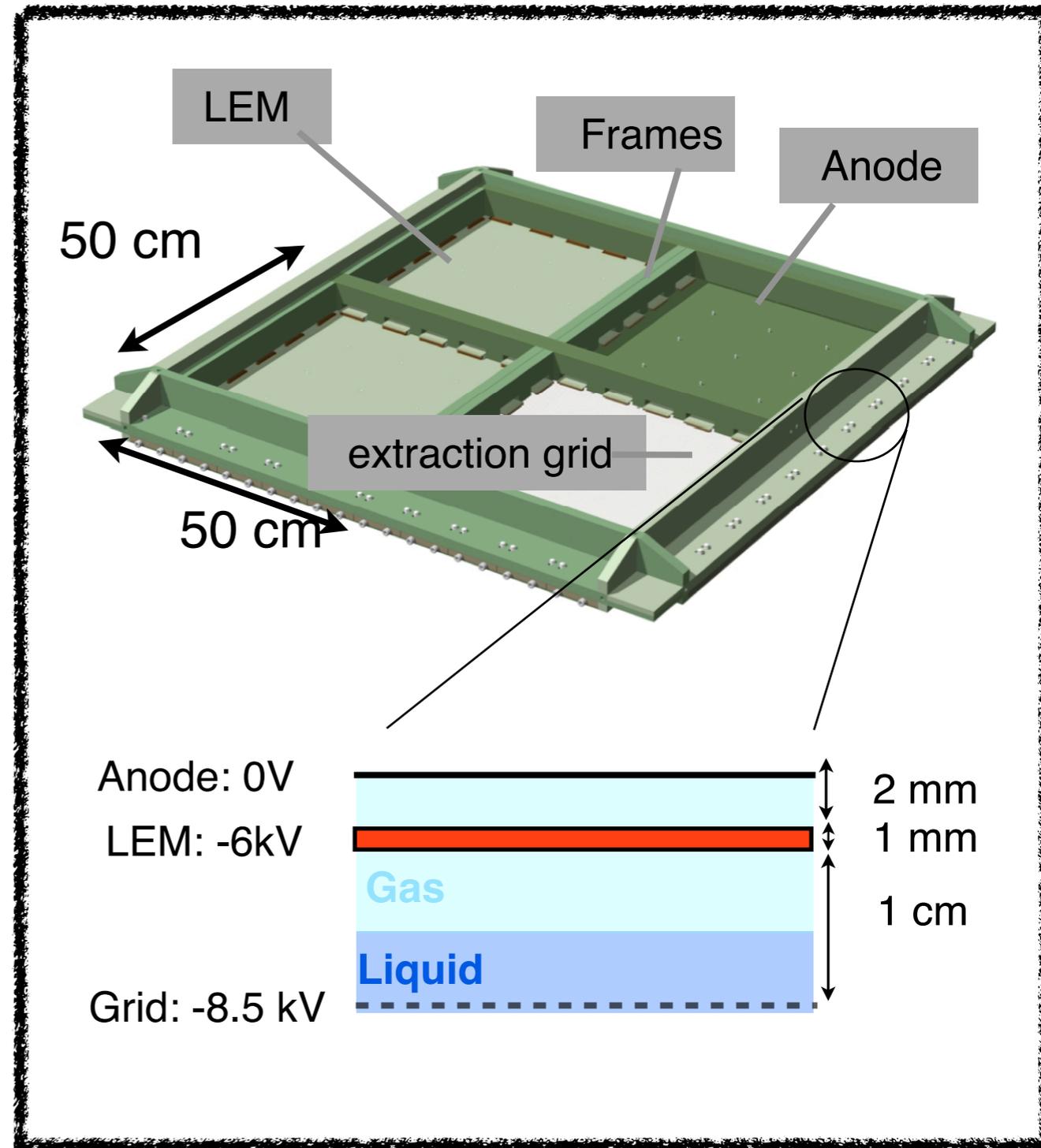
5 GeV nu_mu



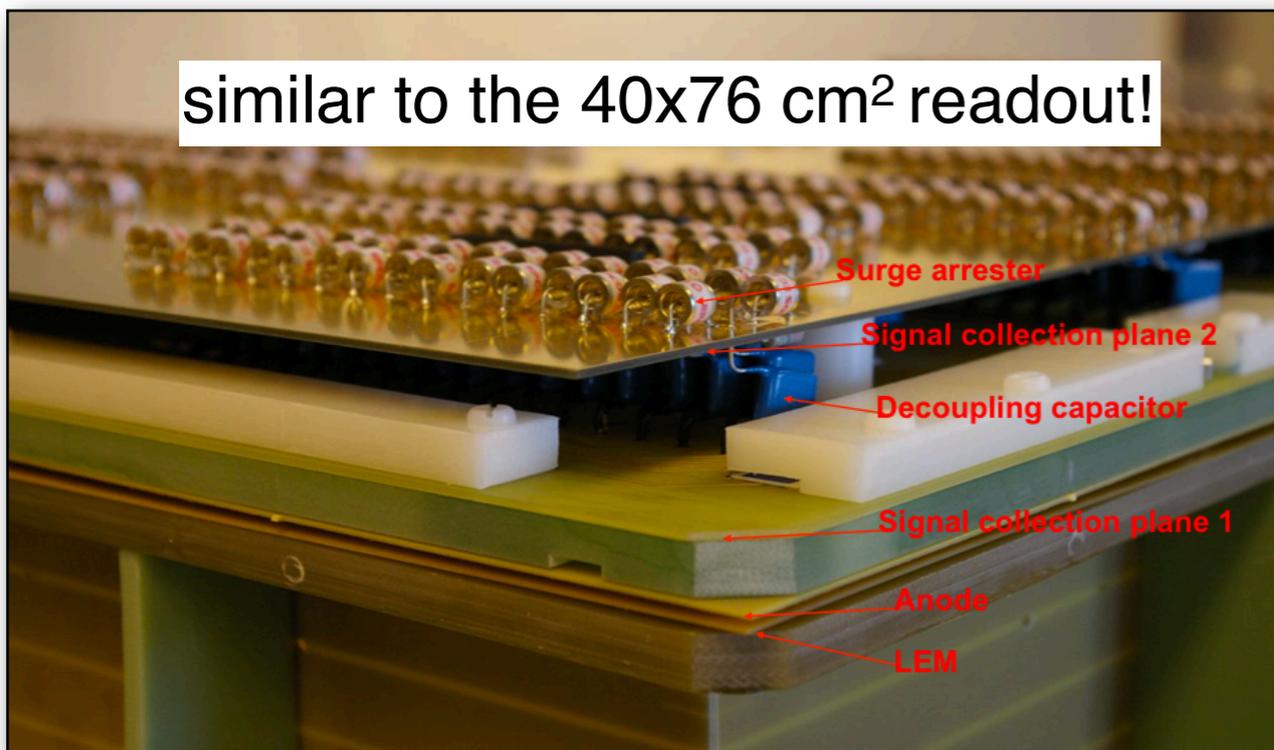
test reconstruction algorithms on data from charged particle beam

ILC PANDORA particle flow algorithms currently being adapted to LAr

- * Independent modules of 50x50 cm².
- * Single extraction grid.
- * LEM 1mm thick 500 um holes 800 um pitch.
- * Anode with ~200 pF/m
- * Front end readout electronics
- * Overall Mechanical structure



similar to the 40x76 cm² readout!



- * LBNO has been put forward to CERN with **unique physics potentials**, including astro-particle physics and proton decay search.
- * Significant R&D efforts and results towards large Double LAr detectors:
 - * optimization of the charge readout.
 - * Good performance of low capacitance PCB anode.
 - * reached gains higher than 90.
 - * Chosen working point with gain about 15 is stable over a period of several weeks.
- * We are now proposing a demonstrator for the double phase LAr technology at a relevant scale $6 \times 6 \times 6 \text{m}^3$ (216m^3).

Thank you!

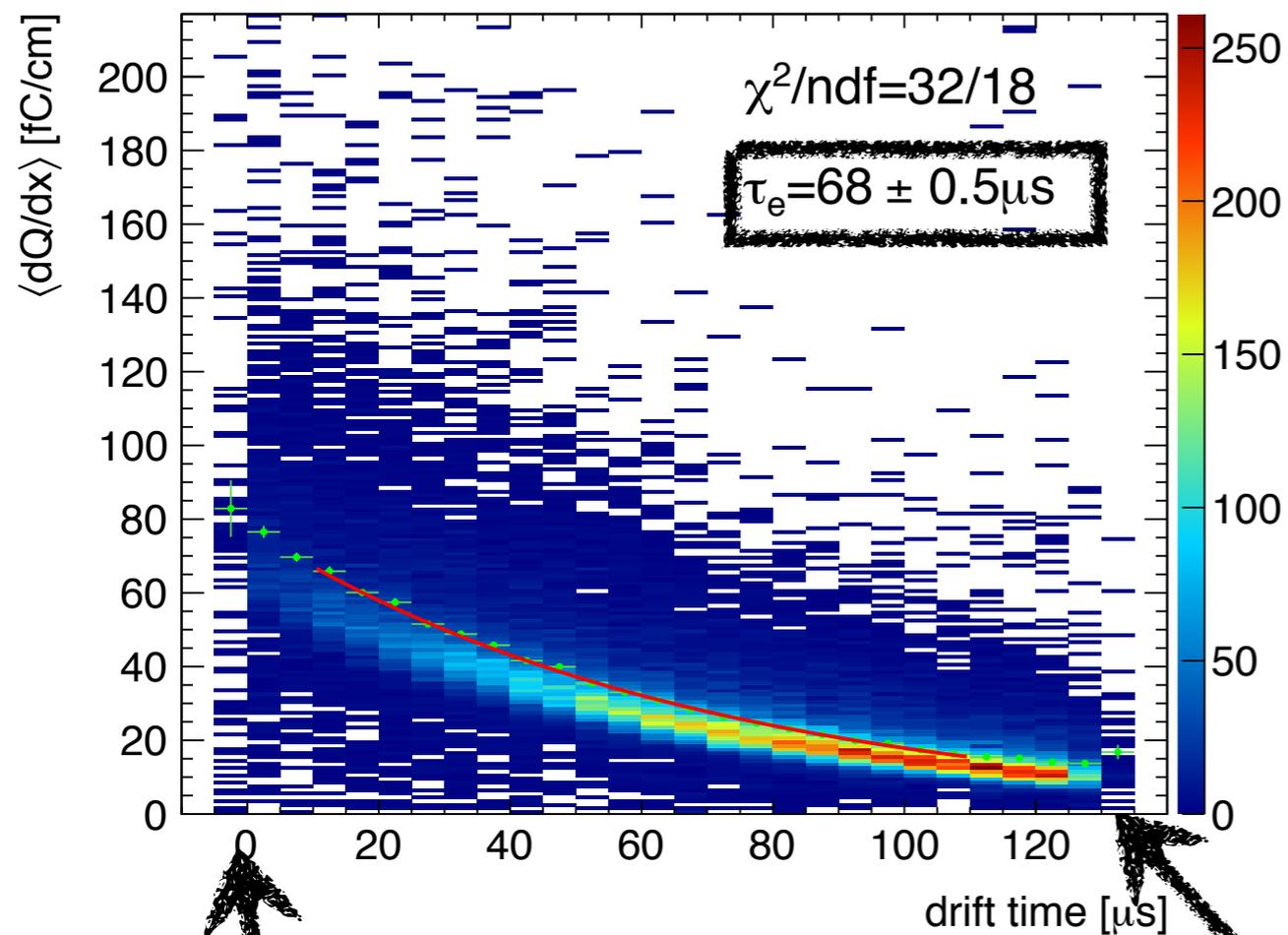


backup

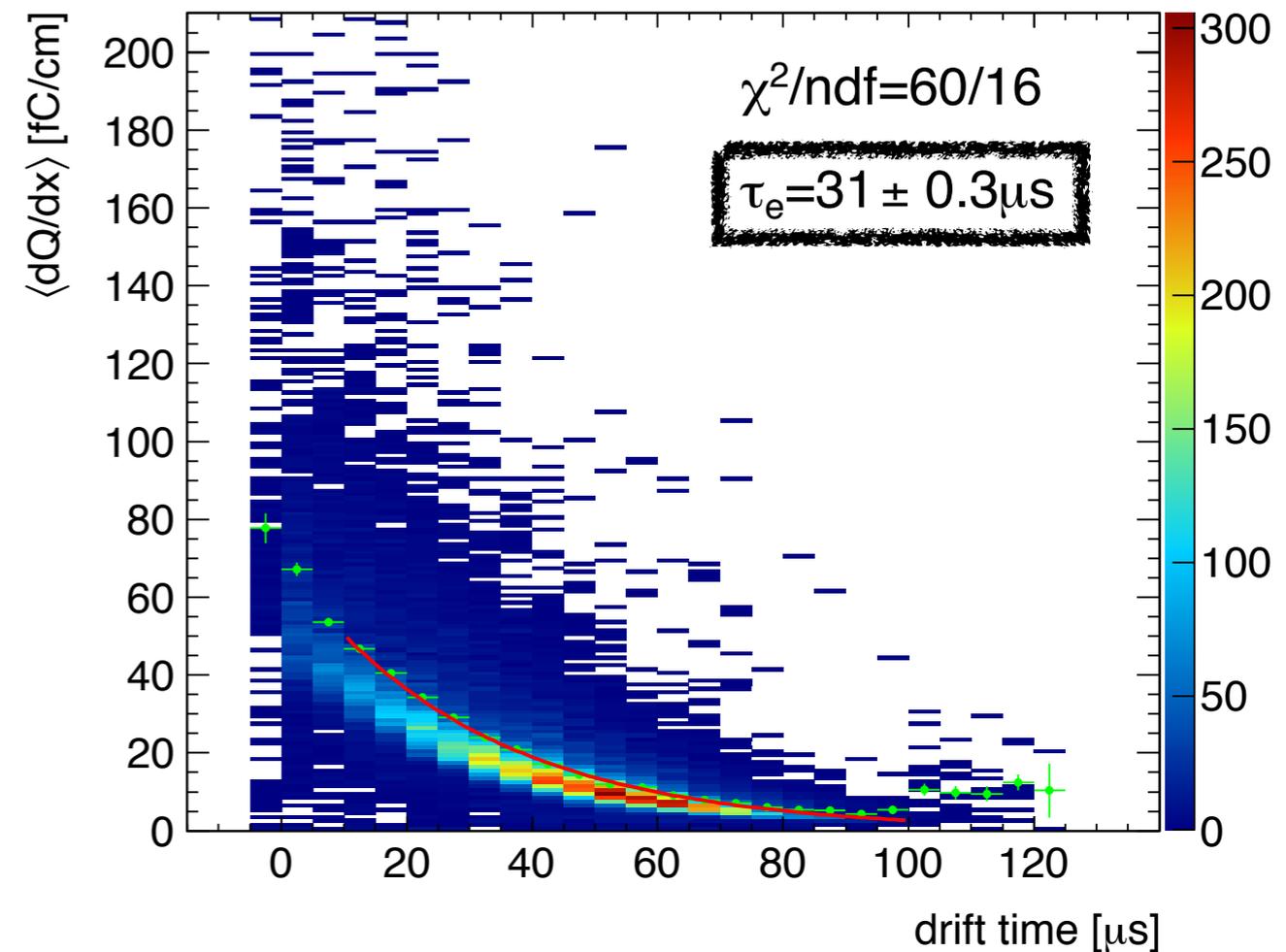
drifting electrons are trapped by impurities in LAr:

$$dQ/dx \propto \exp(-t_{\text{drift}}/\tau_e)$$

towards the beginning of a run



towards the end of a run



top of the chamber

bottom of the chamber

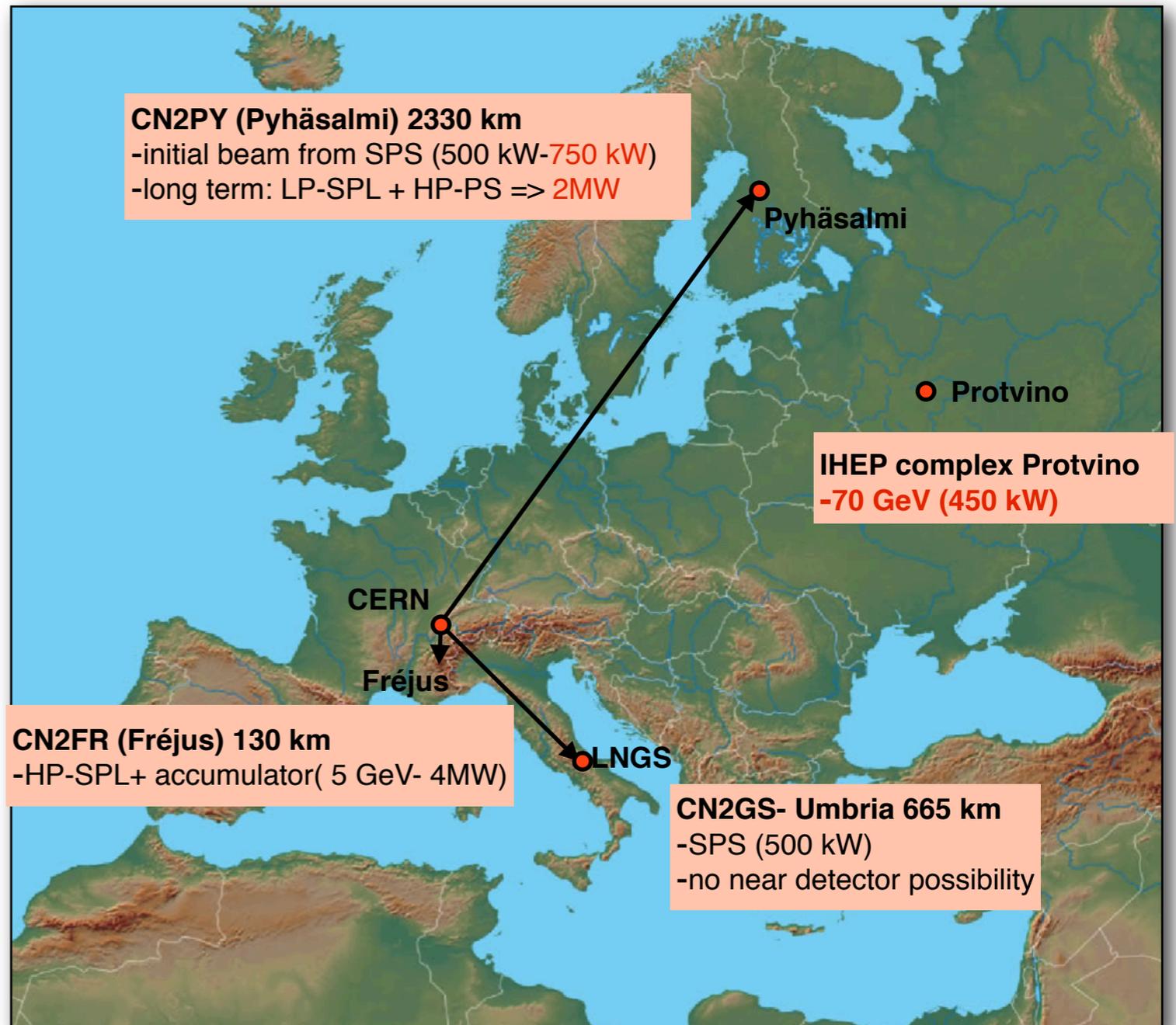
***Option 1:** Pyhäsalmi mine, privately owned, 4000 m.w.e overburden, excellent infrastructure for deep underground access.

***Option 2:** Fréjus, nearby road tunnel, 4800 m.w.e overburden, horizontal access. no MH, counting only experiment on $\nu \bar{\nu}$ asymmetry

***Option 3:** Umbria (LNGS extension), 2000 m.w.e overburden, horizontal access. CNGS off-axis beam

*Beams

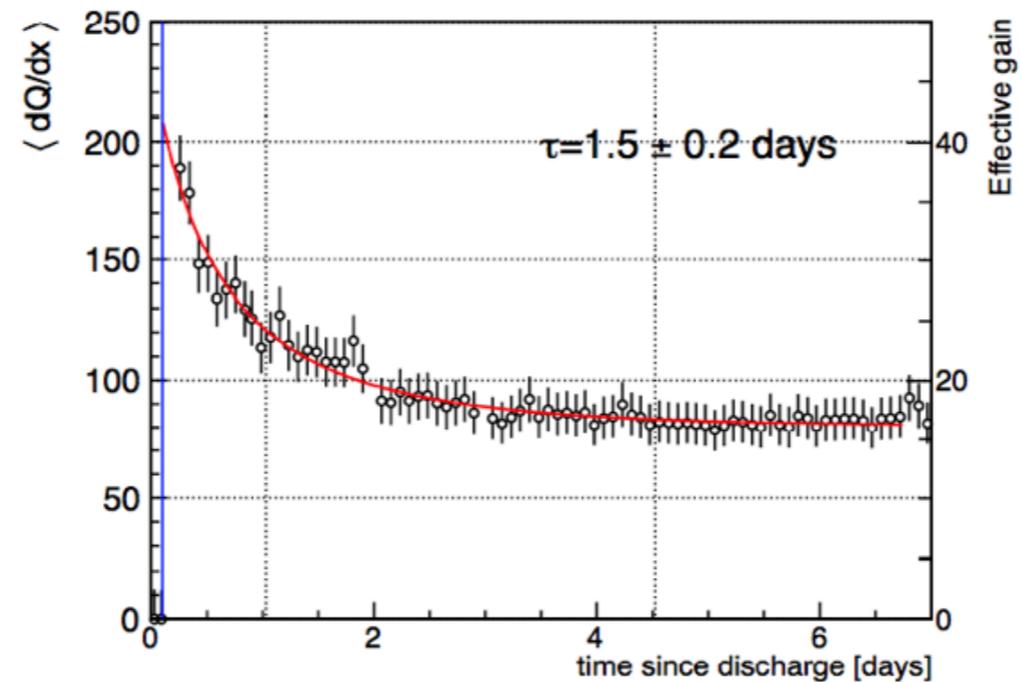
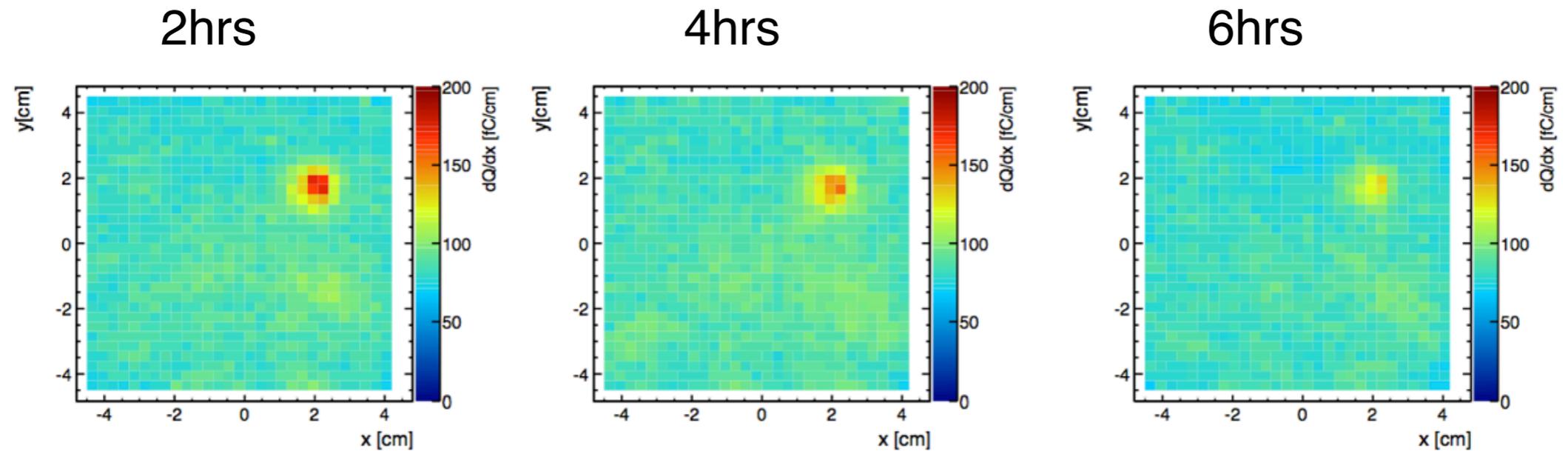
- Design of new CERN conventional neutrino beam to Finland (CN2PY) Baseline = 2300 km
- Upgrades of CERN SPS to 700kW
- New CERN HP-PS (2MW@50 GeV) -
- Recently: assessment of a new conventional beam coupled to accelerator upgrade at Protvino, Russia (OMEGA project) – Baseline = 1160 km



A new massive deep underground neutrino observatory for long baseline neutrino studies, capable of proton decay searches, atmospheric and astrophysical neutrino detection

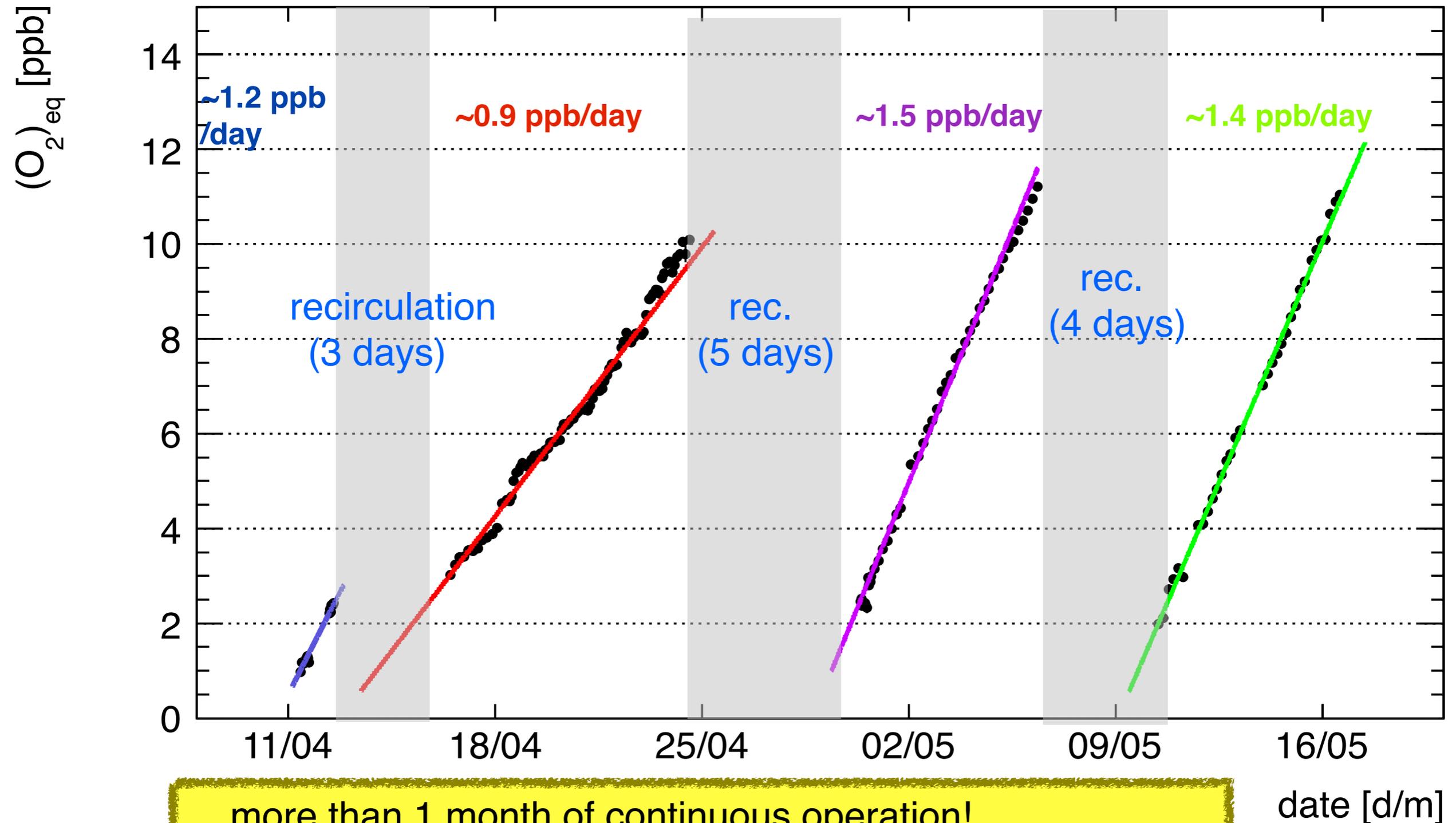
Local vs global gain evolution

time after discharge



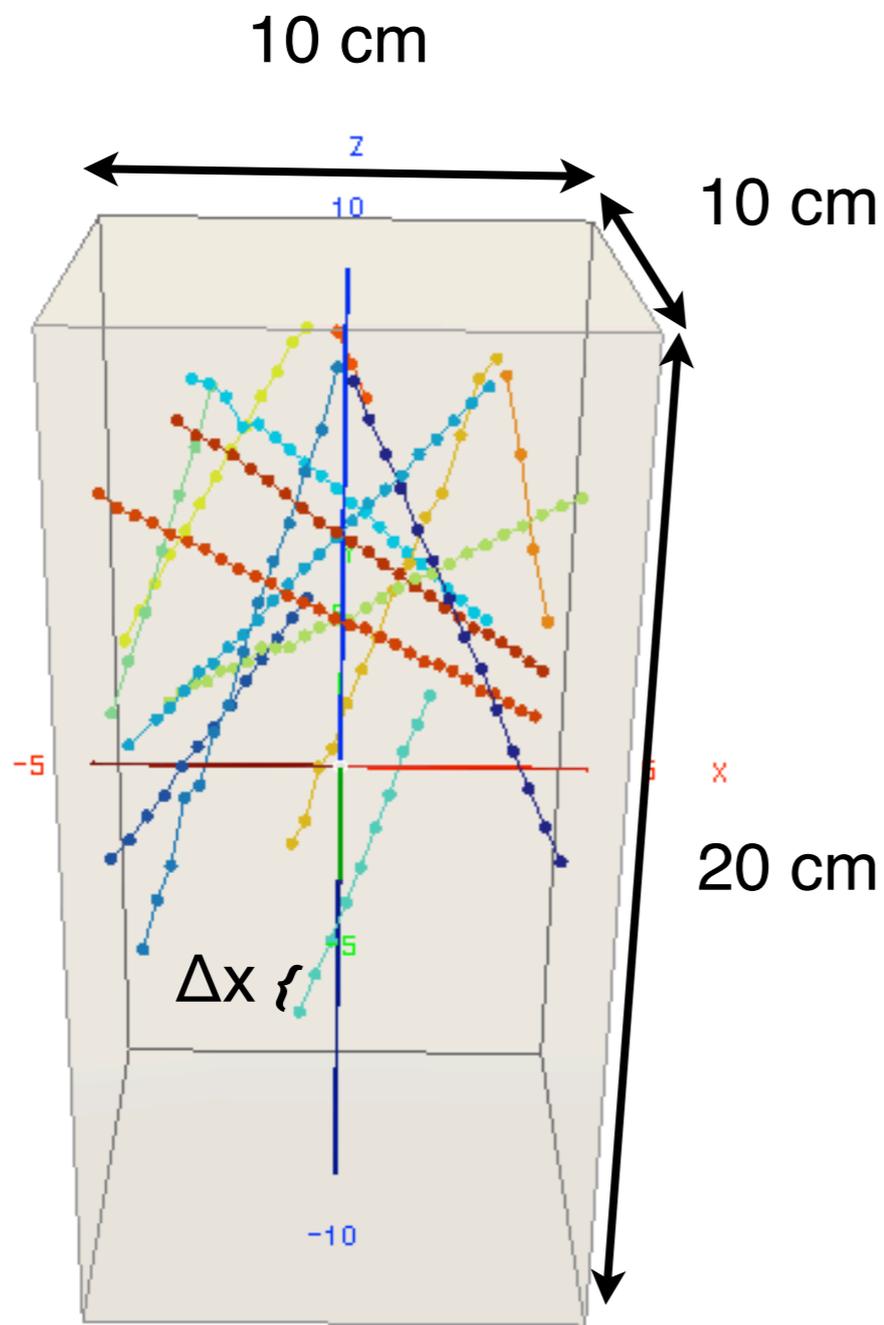
Impurities in the liquid: $[O_2]_{eq} \approx 300 \mu s / \tau_e$

4 runs. few days of gas recirculation between each run.

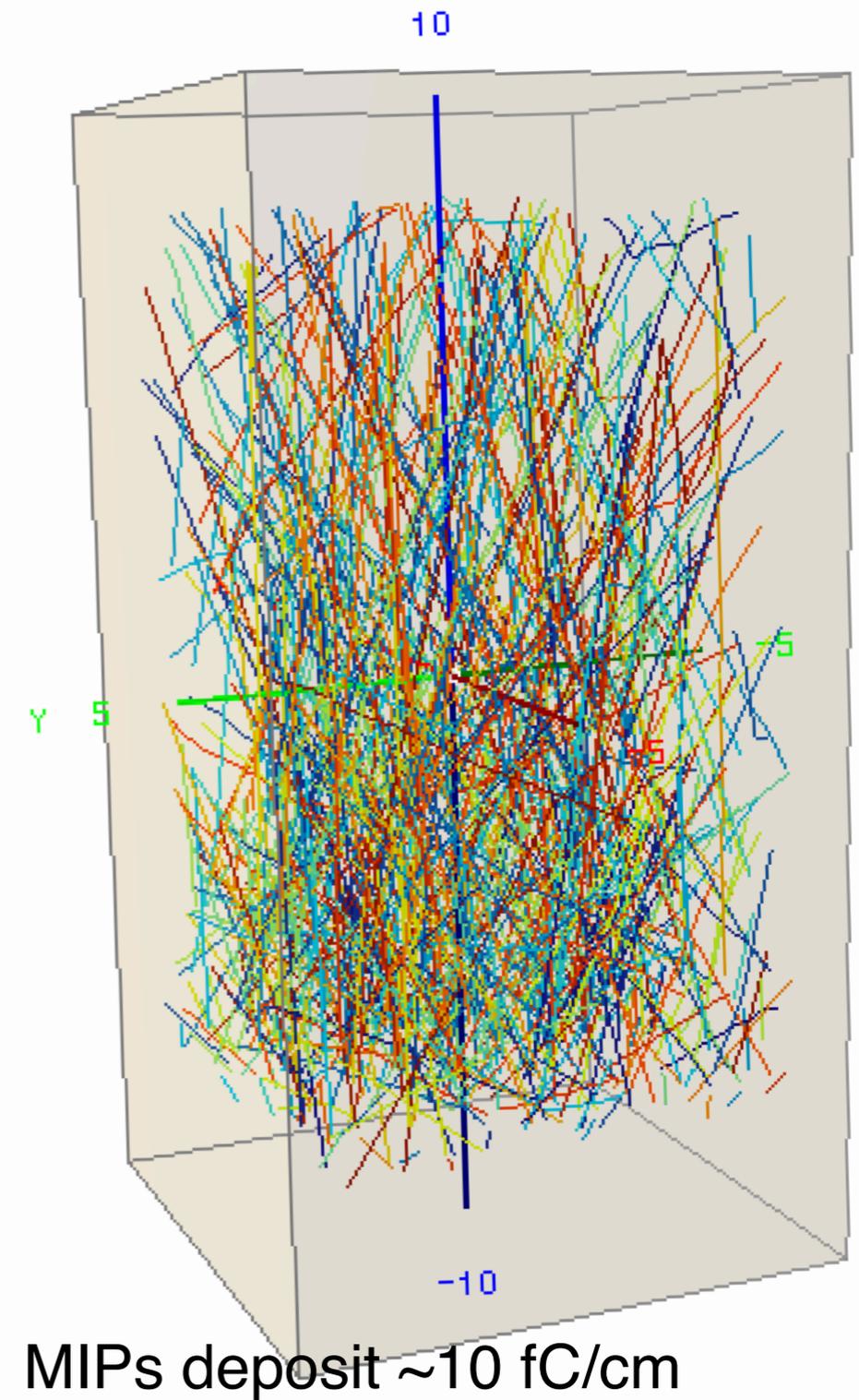


3D Track reconstruction

→ ΔQ and Δx (3 dimensional track segment!) for each view, literature: $\Delta Q/\Delta x = 10$ fC/cm (mip)



large statistics!



***Proof of principle with 10x10 cm² double phase Ar LEM-TPC prototype:**

A. Badertscher et al., "Operation of a double-phase pure argon Large Electron Multiplier Time Projection Chamber: Comparison of single and double phase operation" NIM A617 (2010) p.188-192

A. Badertscher et al., "First operation of a double phase LAr Large Electron Multiplier Time Projection Chamber with a two-dimensional projective readout anode" NIM A641 (2011) p.48-57

***First successful operation of a 40x80 cm² device in November 2011:**

A. Badertscher et al., "First operation and drift field performance of a large area double phase LAr Electron Multiplier Time Projection Chamber with an immersed Greinacher high-voltage multiplier" JINST 7 (2012) P08026

A. Badertscher et al., "First operation and performance of a 200 lt double phase LAr LEM-TPC with a 40x76 cm² readout", JINST 8 (2013)P04012, available at <http://dx.doi.org/10.1088/1748-0221/8/04/P04012>

***10x10 cm² double phase Ar LEM-TPC prototype: further R&D towards final, simplified charge readout for GLACIER:**

first results presented TPC-symposium, Paris Dec. 2011

***Future:**

1x1x3 m³ prototype to test feasibility of large area readouts.

6x6x6 m³ prototype to be operated at CERN NA in a charged particle beam.

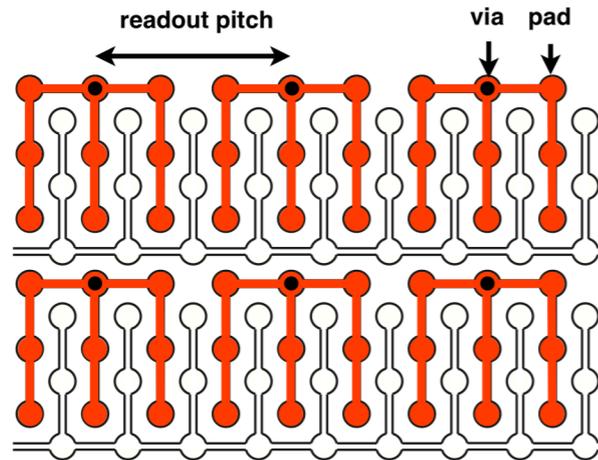
Final goal:

Giant LAr LEM TPC as far detector for a Long Baseline Neutrino Oscillation (LBNO) experiment (SPSC-EOI-007)

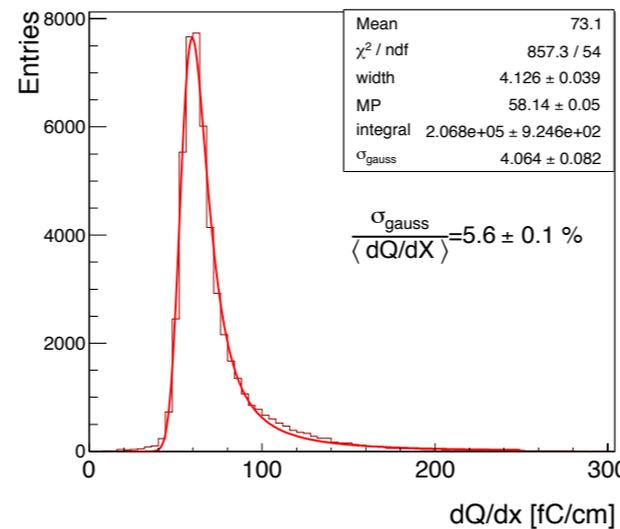
Various anode designs were tested

anode A

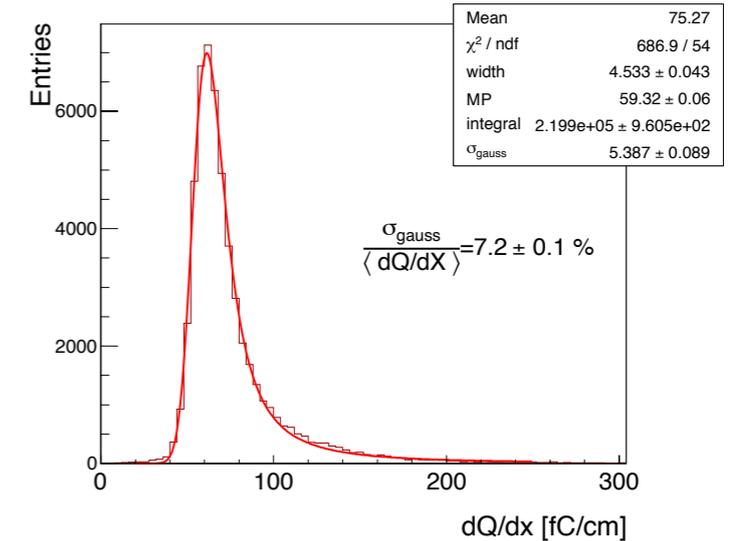
~200 pF/m



view 0 (red)

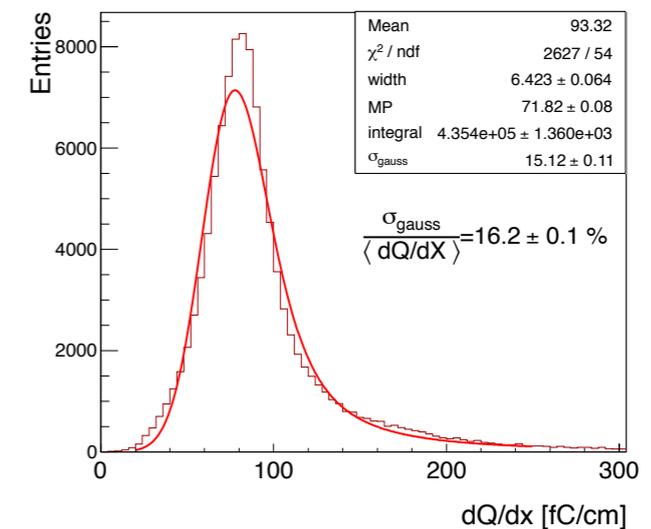
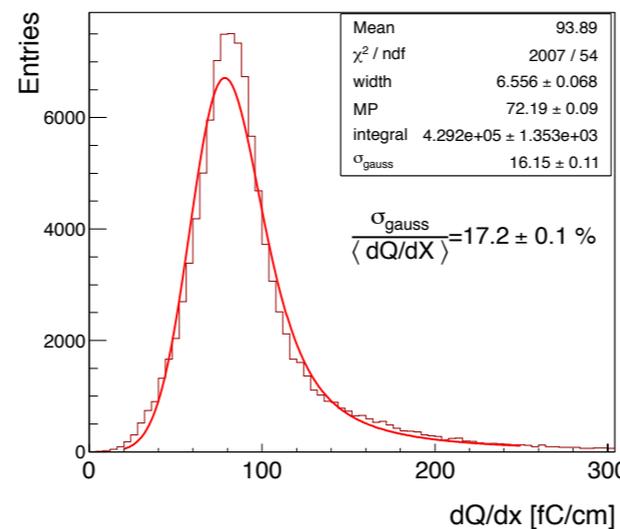
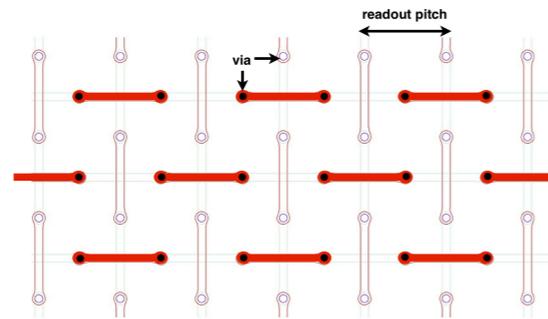


view 1 (white)



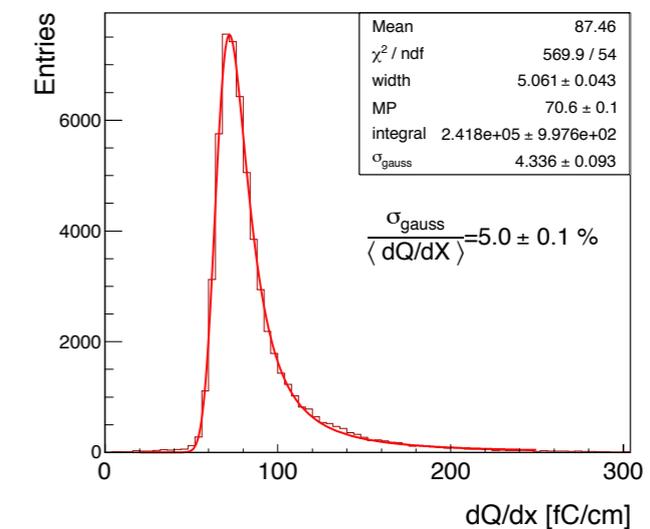
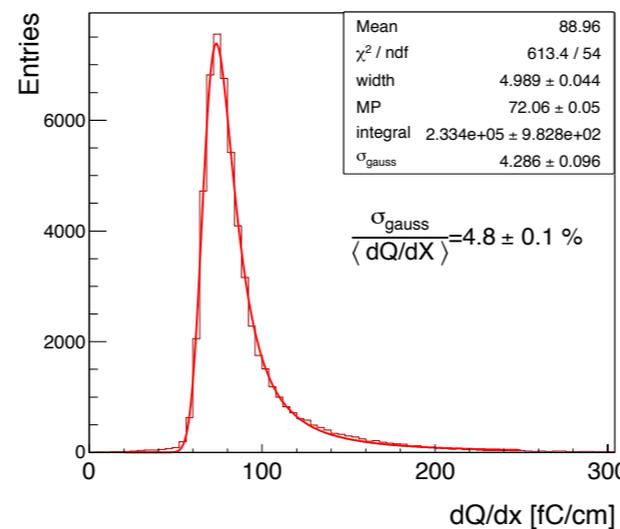
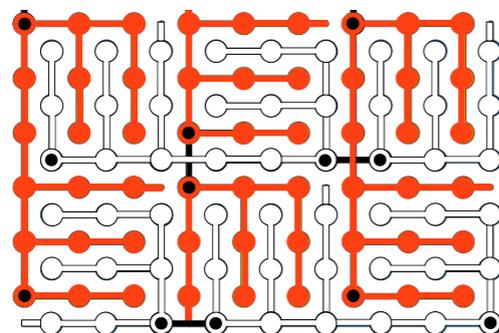
anode B

~100 pF/m



anode C

~200 pF/m



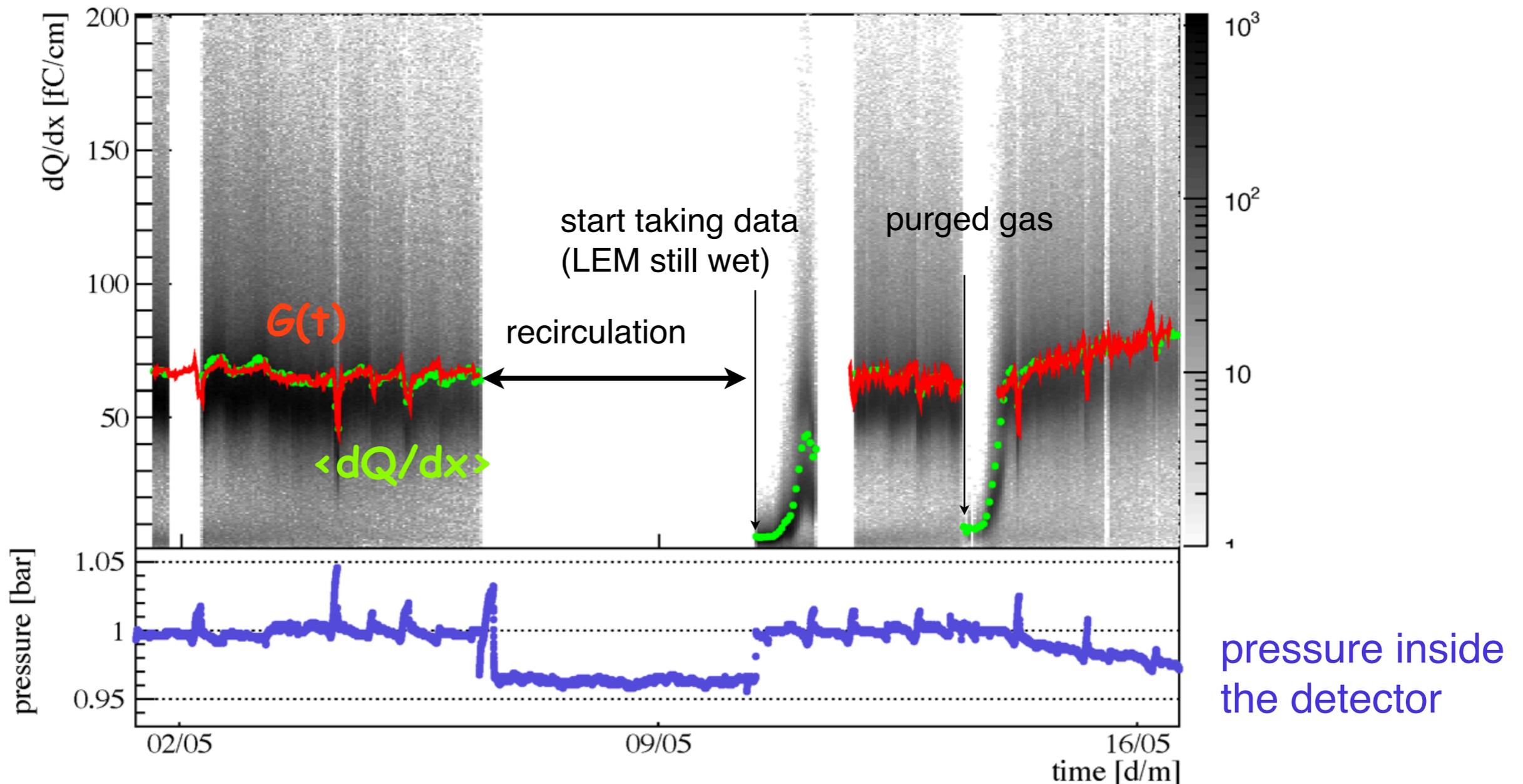
Stability of the gain

Gain in the LEM depends on:

- * density of the gas (=pressure, temperature)
- * the electric field across the LEM
- * on effective path across the LEM = x

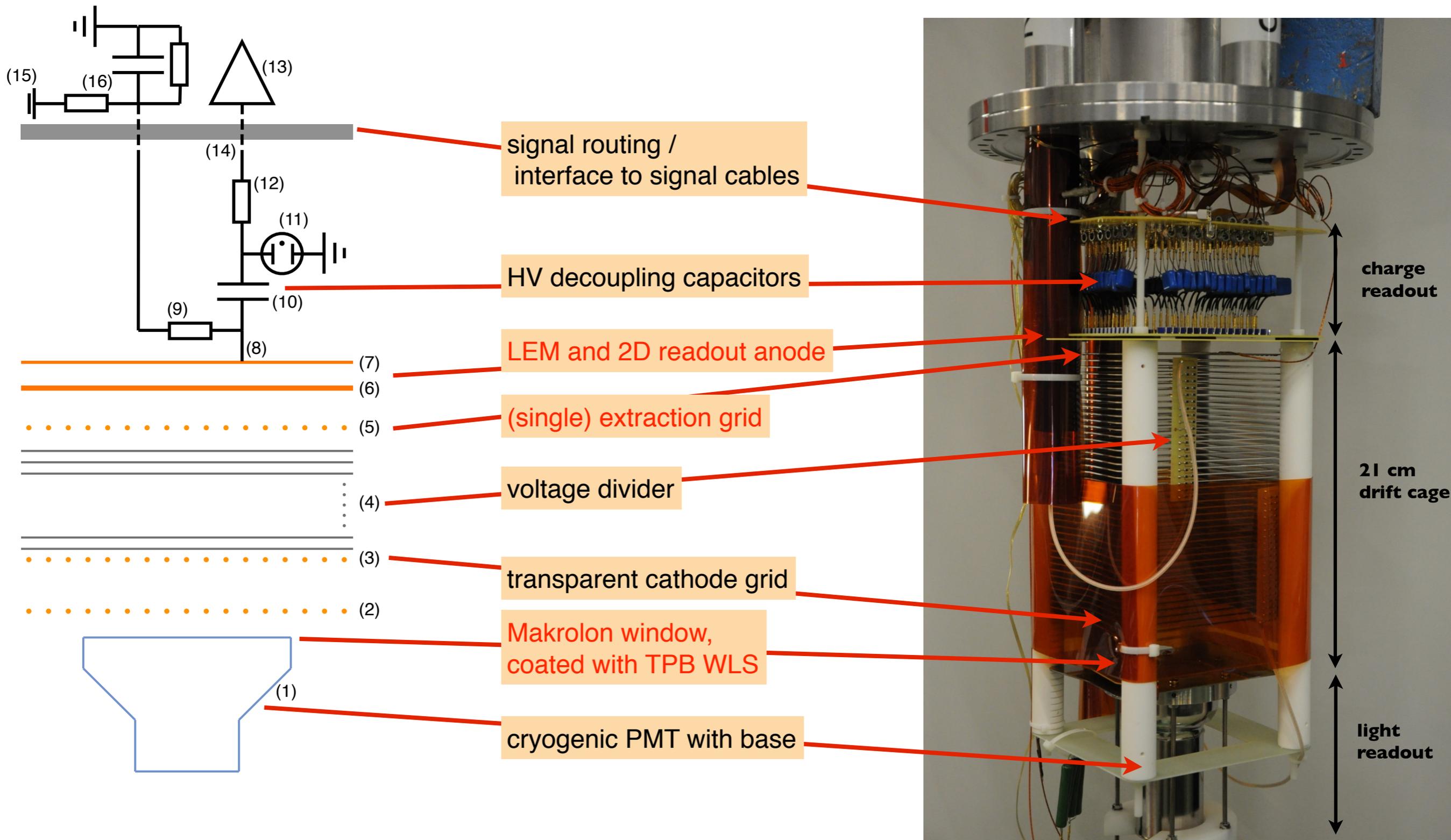
Well described by the function:

$$G(t) = \text{trans.} \times e^{x \cdot \alpha(p, T, E)} \quad \text{with} \quad \alpha(p, T, E) = \frac{Ap}{T} e^{-\frac{Bp}{E}}$$



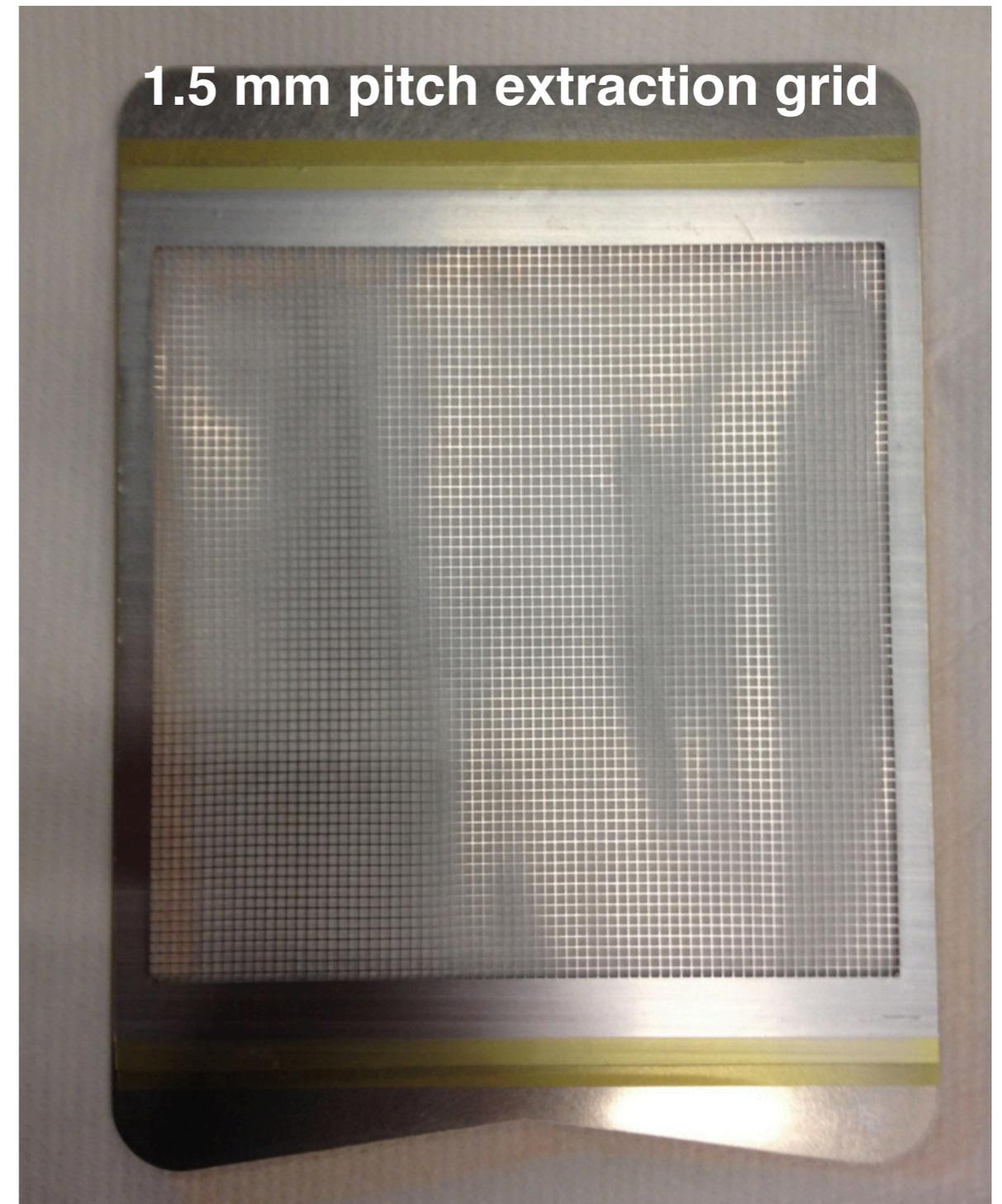
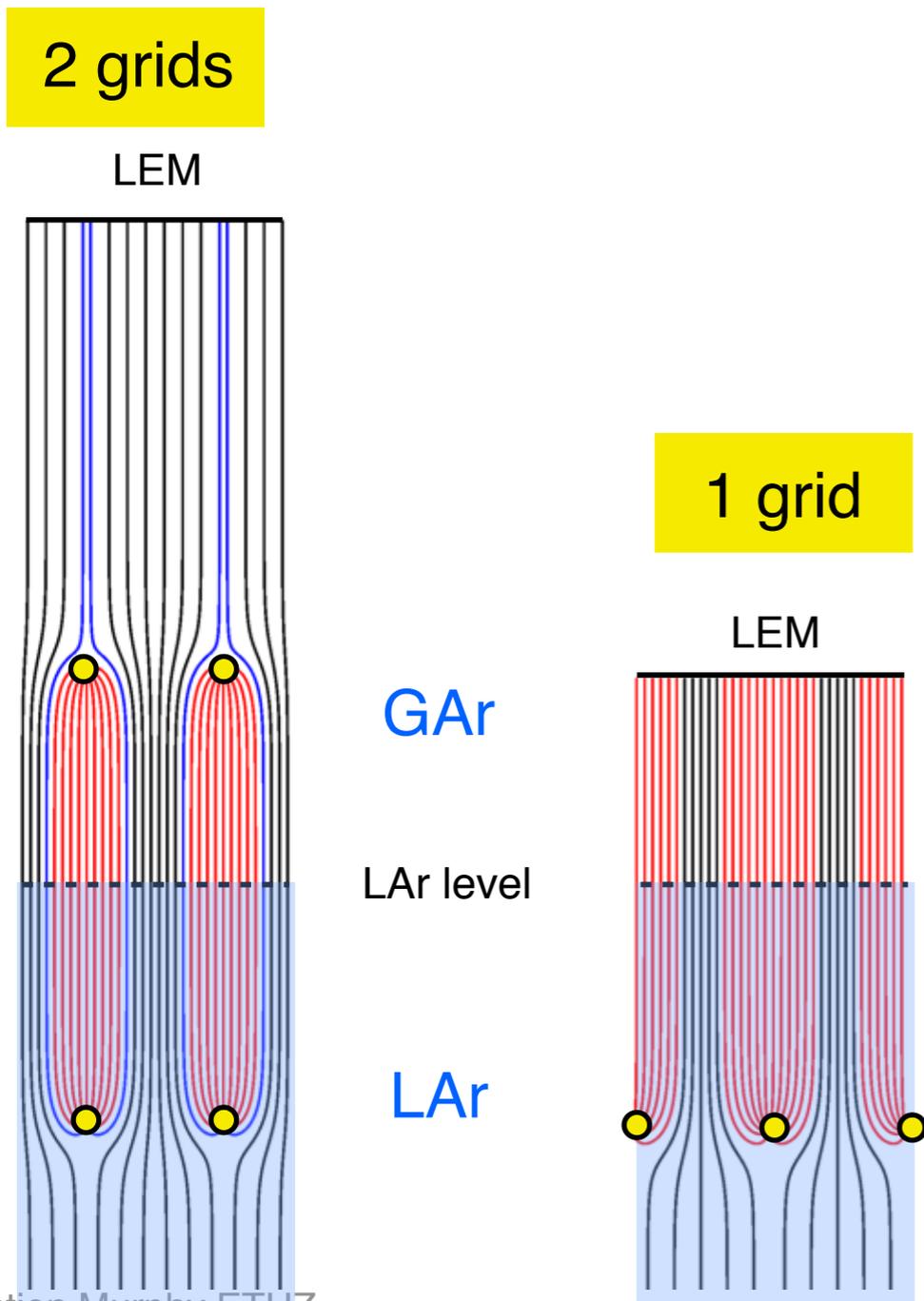
Future detectors will operate under controlled pressure environment!

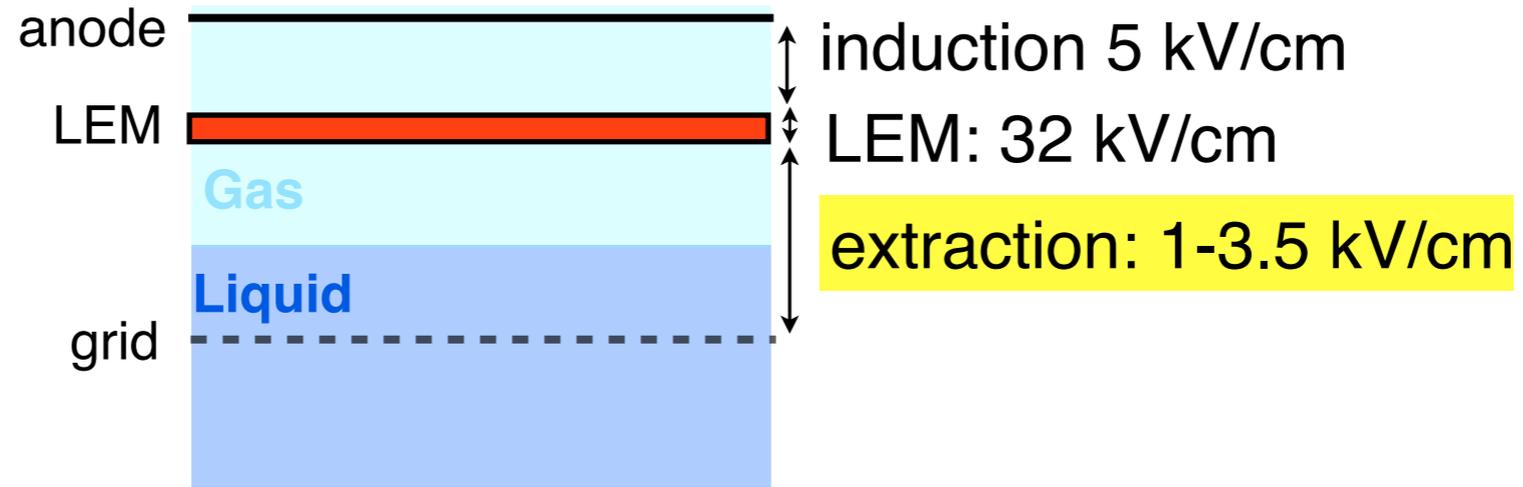
10x10x20 cm³ prototype: overview



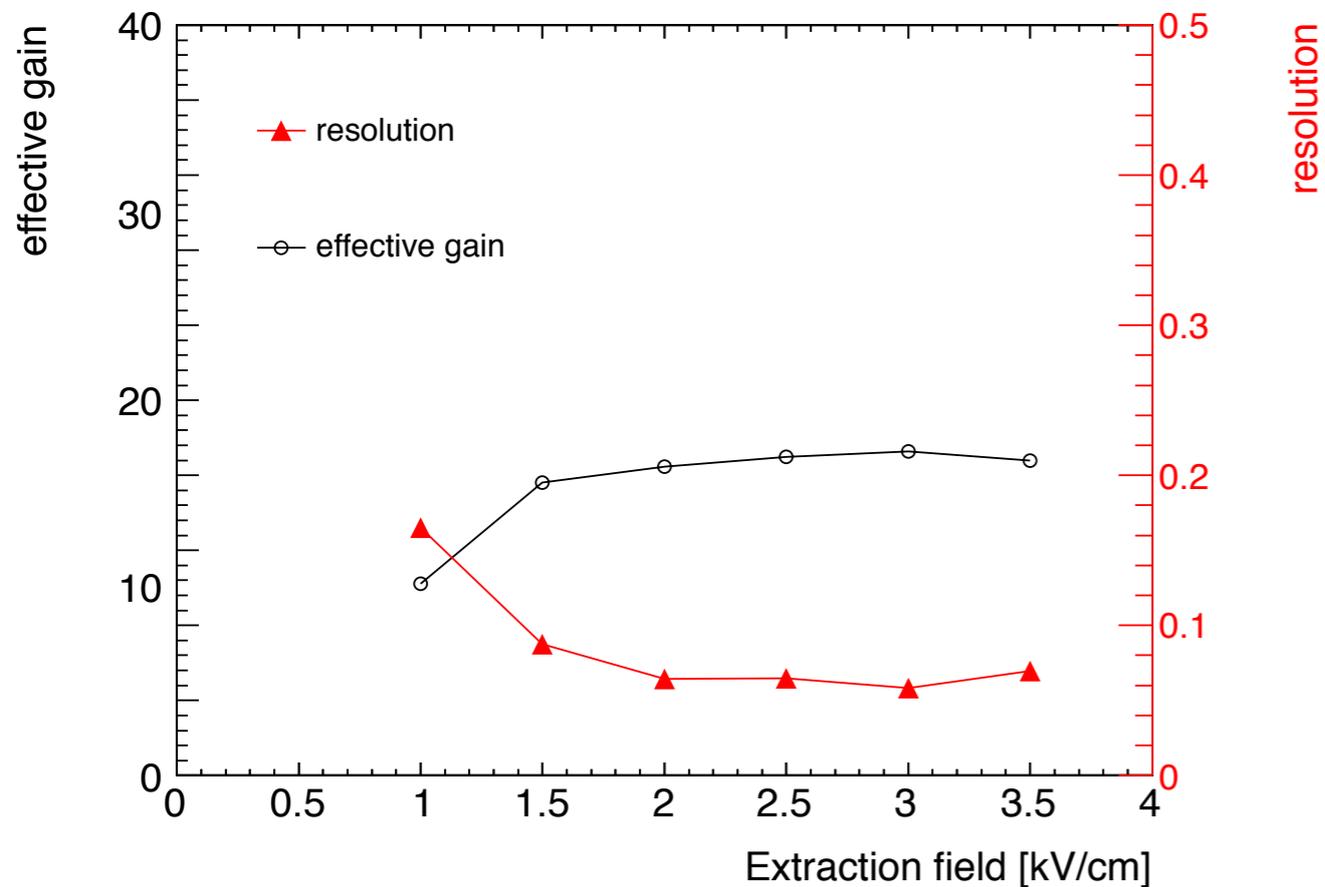
ETH Simplifying the design- single extraction grid

- * Simplified scheme
- * Higher transparency possible (no alignment of grids needed)
- * Less absolute voltage

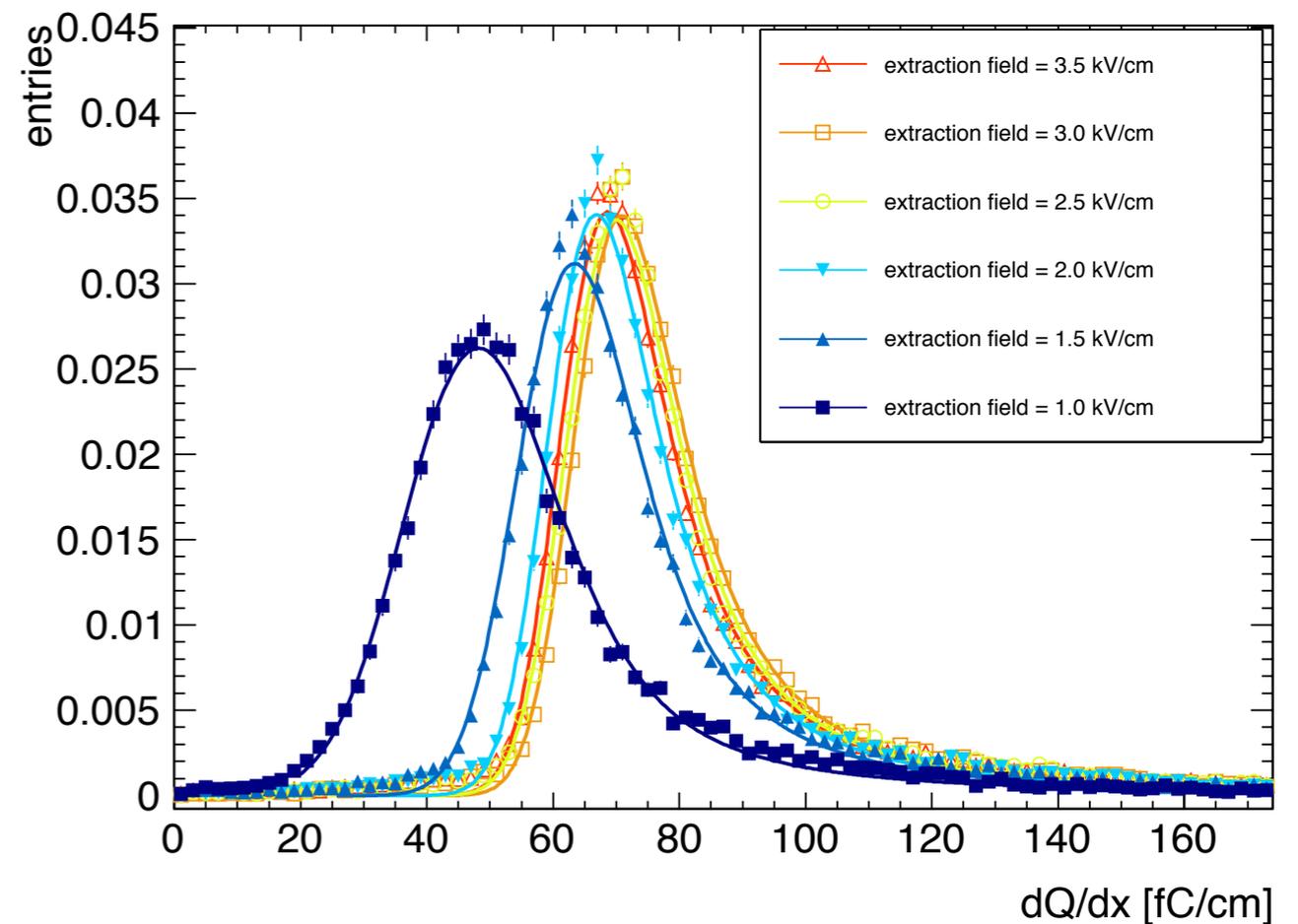




gain and resolution for diff. extr. fields

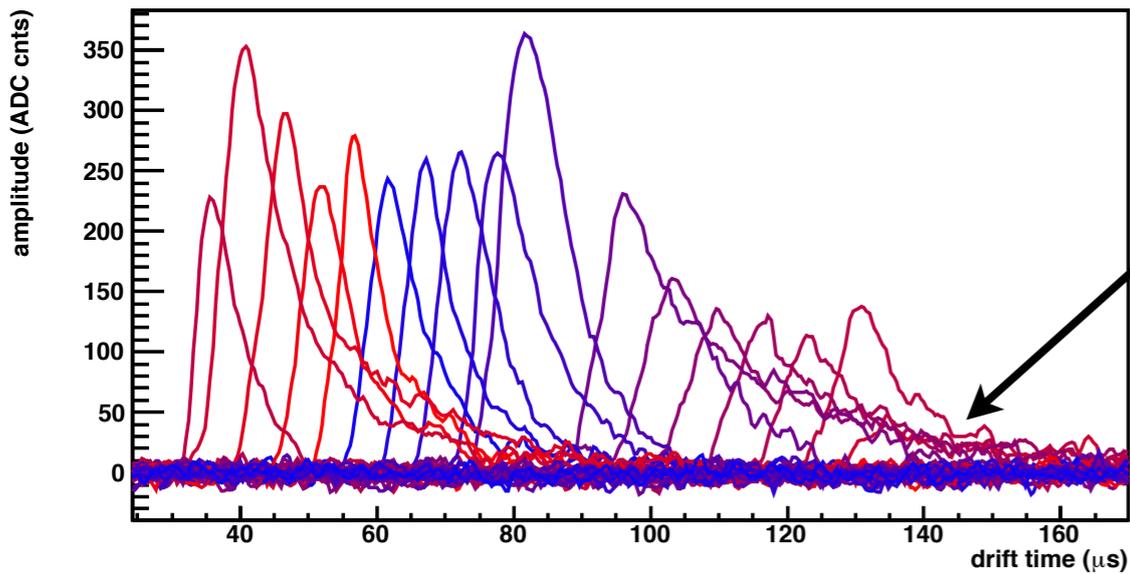


Landau distributions for diff. extr. fields



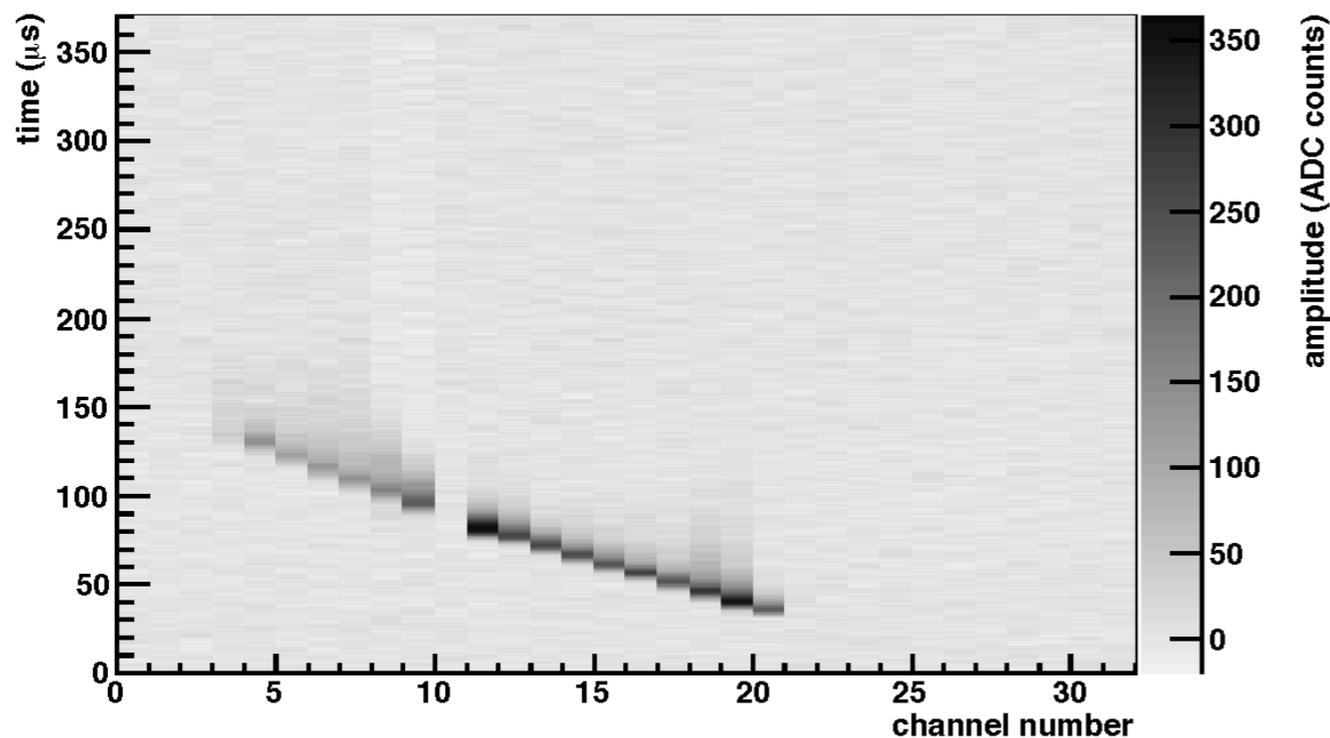
What happens at low extraction fields?

View 1: Signals (run 15957, event 6)

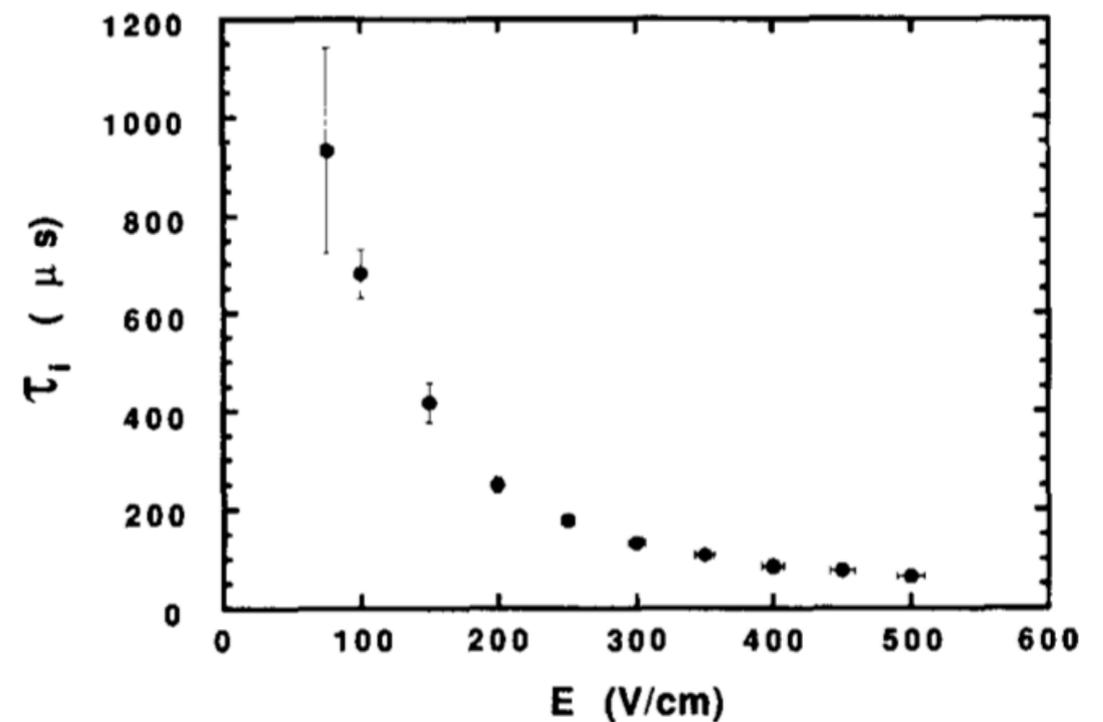


tails, due to slow electron emission at low fields (here: 1.5 kV/cm)

View 1: Event display (run 15957, event 6)



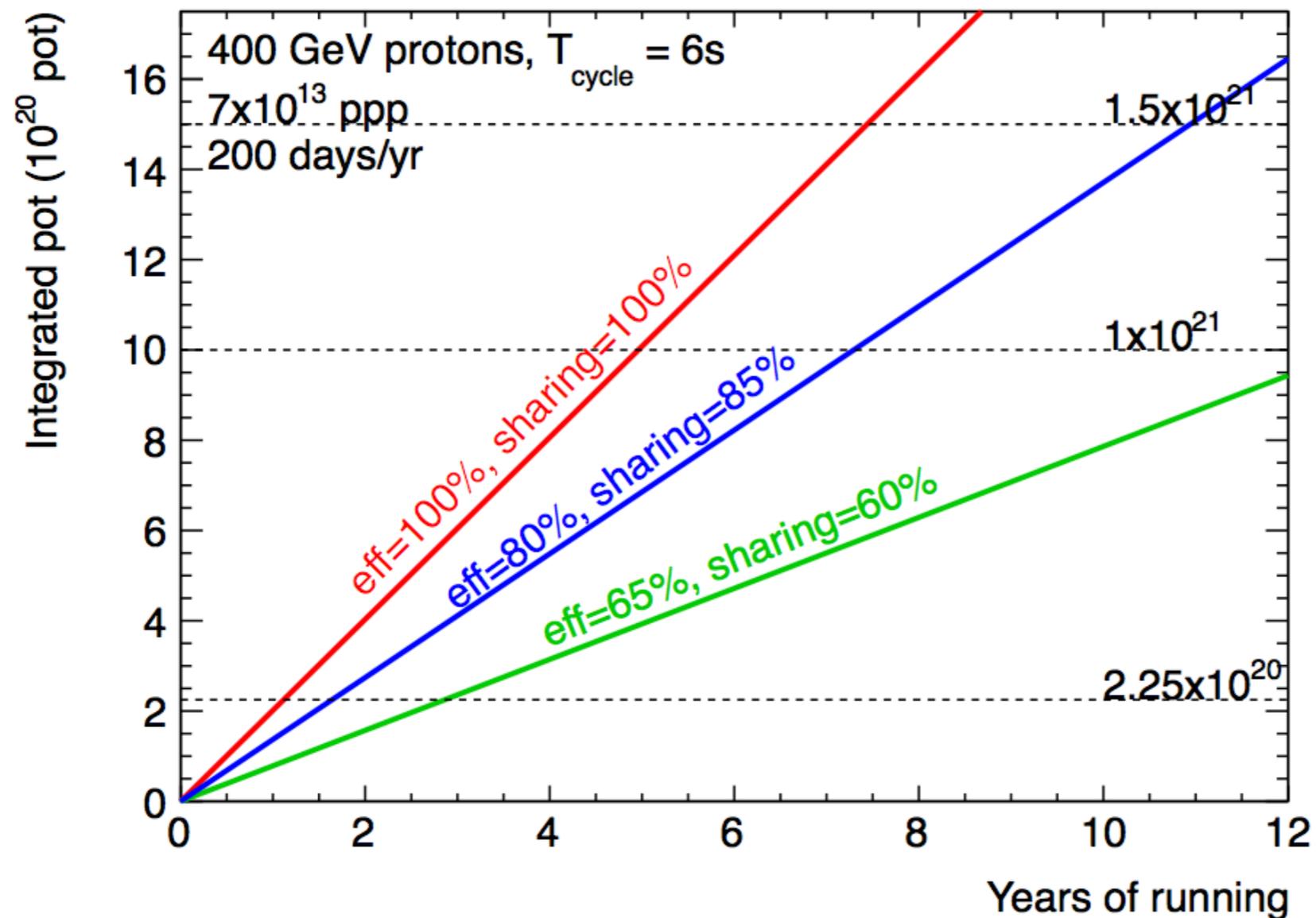
Literature:



Borghesani et al., "Electron transmission through the Ar liquid-vapor interface", Phys. Lett. A149 (9)

CNGS: 4.5×10^{19} protons/year (w/o sharing 7.6×10^{19} protons/year)

LBNO: assume 1.5×10^{21} pot in 12 year $\Rightarrow \sim 1.5 \times 10^{20}$ protons/year from improved SPS intensity (7×10^{13} ppp instead of 4×10^{13} presently) and operation sharing

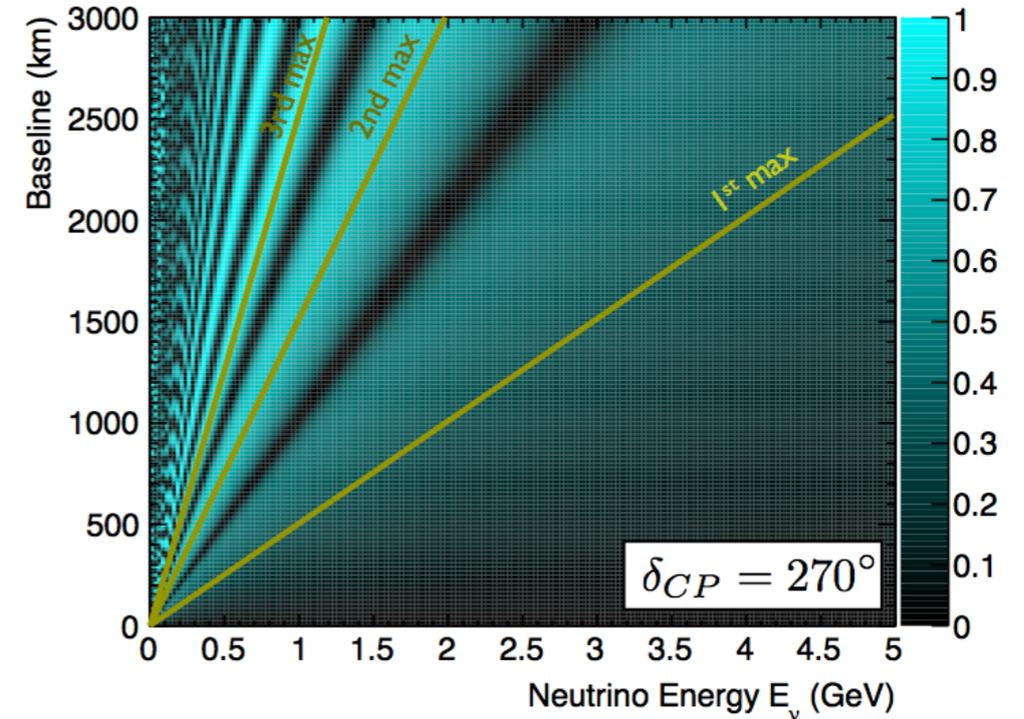


✓ 5 sigma CPV

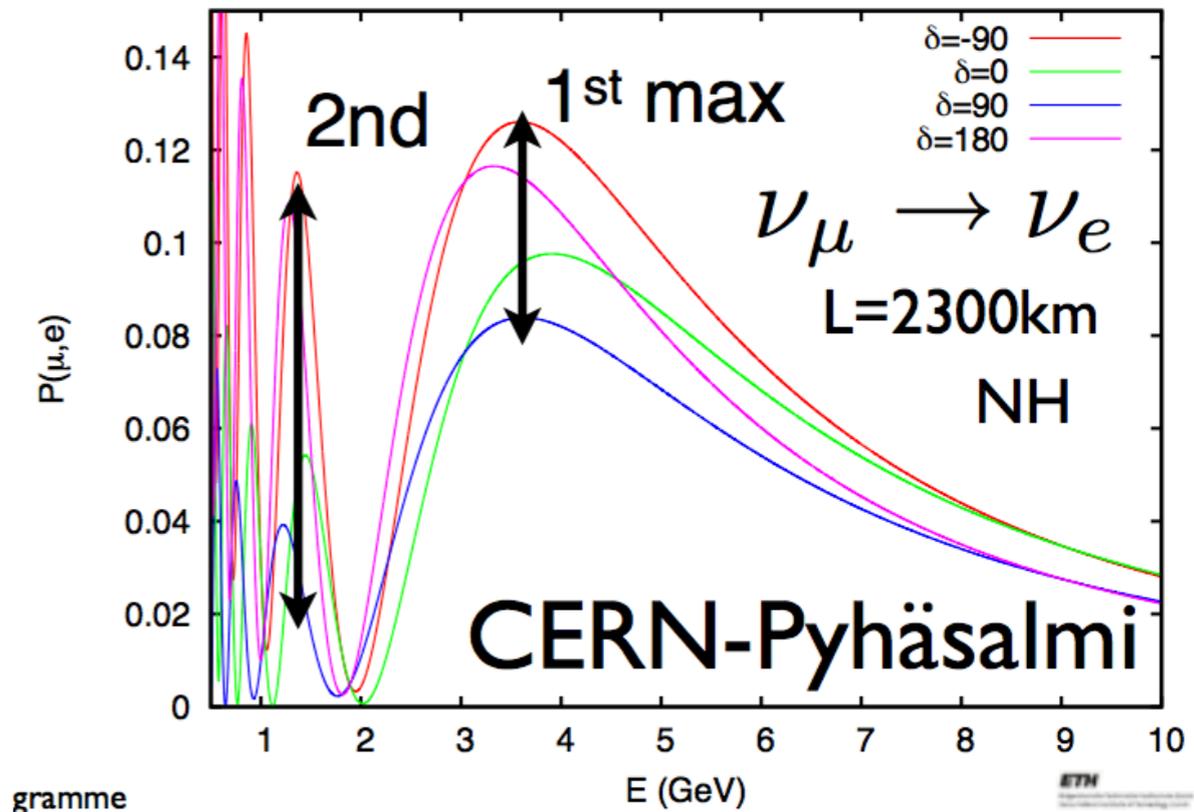
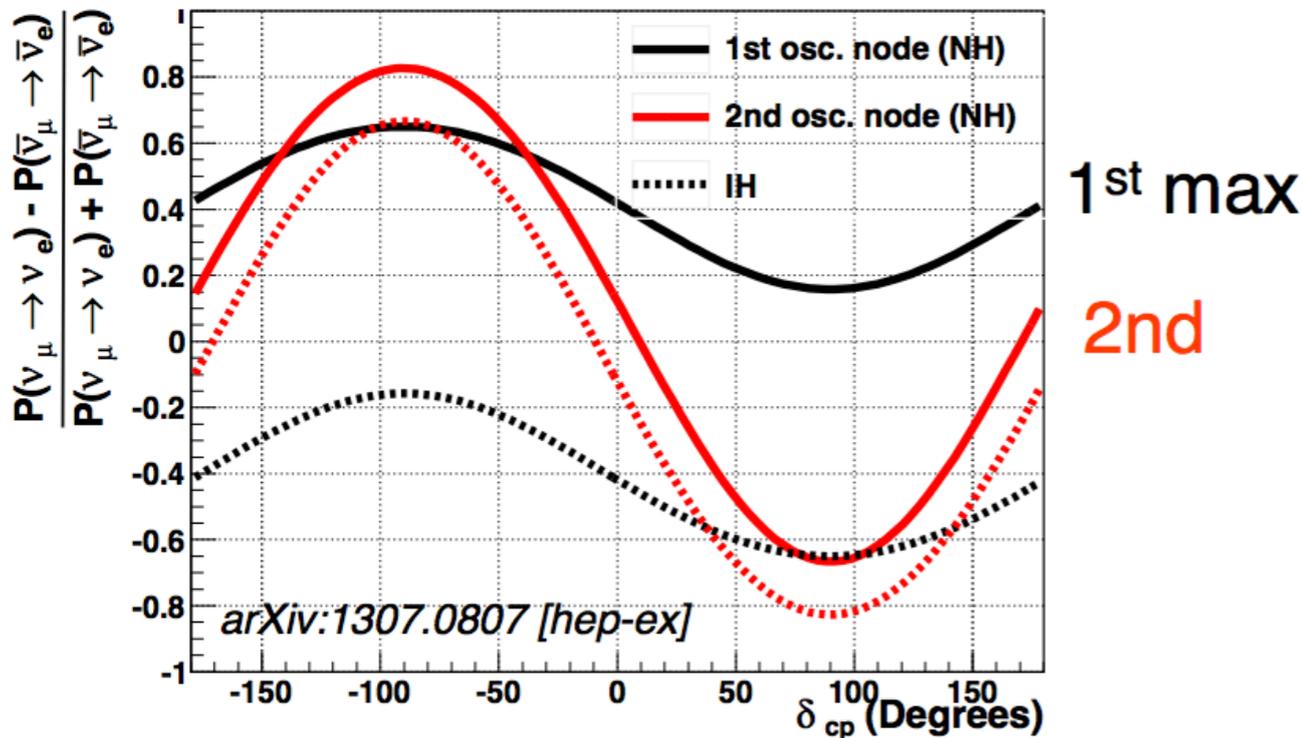
✓ 5 sigma MH

$$\left. \frac{P(\nu) - P(\bar{\nu})}{P(\nu) + P(\bar{\nu})} \right|_{a=0} \approx -\frac{2s_\delta c_{12} s_{12}}{s_{13}} \cot \theta_{23} \frac{\delta m_{21}^2 L}{2E}$$

Growing CP effect with $L/E \Rightarrow$ CP asymmetries larger for 2nd, 3rd .. maxima
 Long baseline (>1000 km) needed



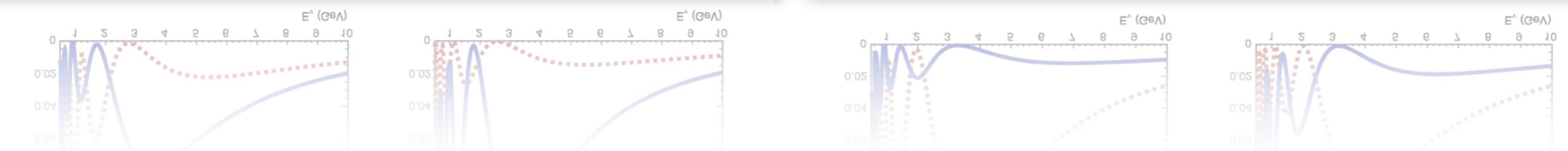
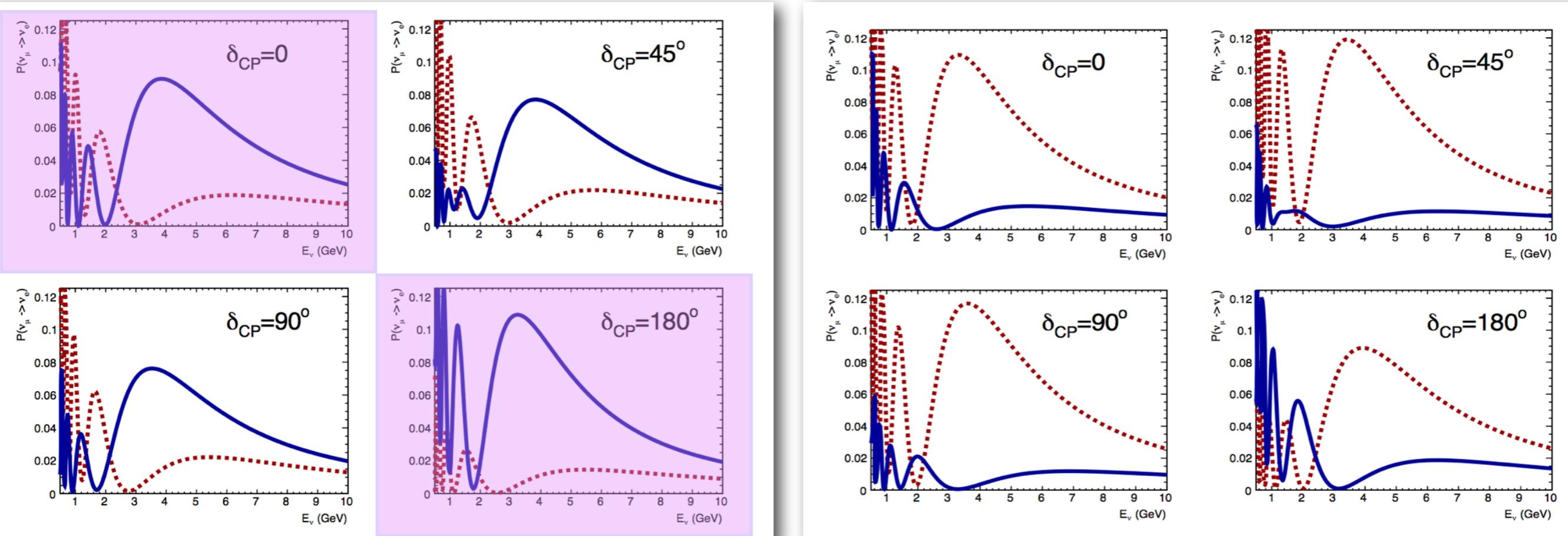
FNAL->homestake (1300 km)



- Long baseline=>complete swap between neutrinos and antineutrinos
- spectral information provides unambiguous determination of osc para and allows to distinguish the two CP conserving scenarios

NH

IH

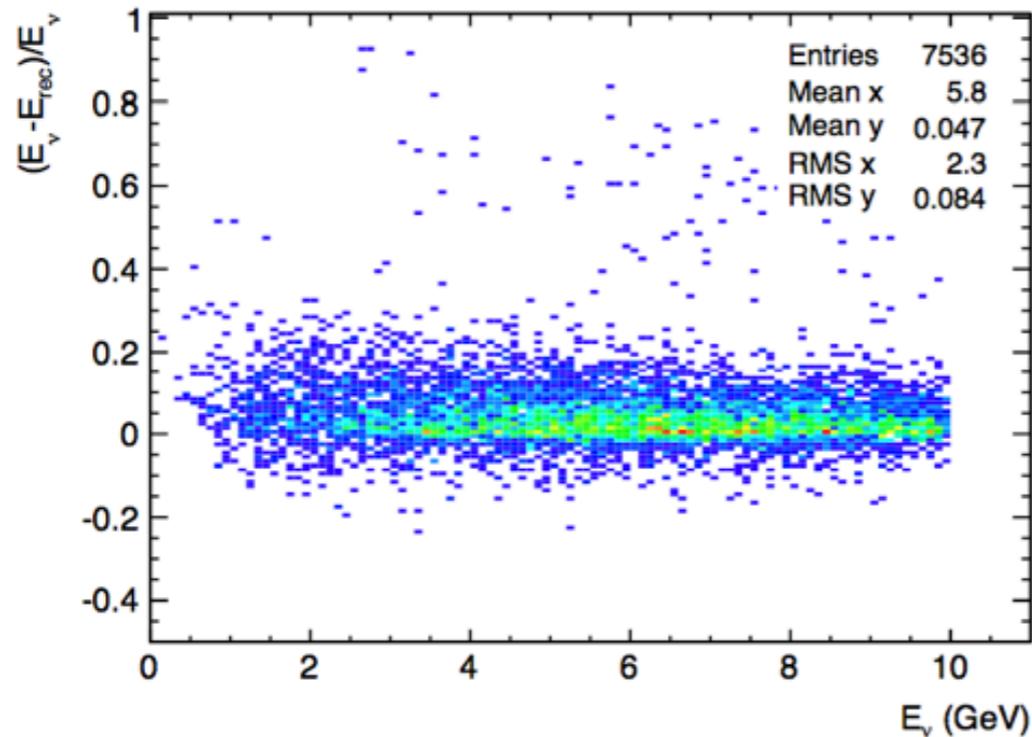
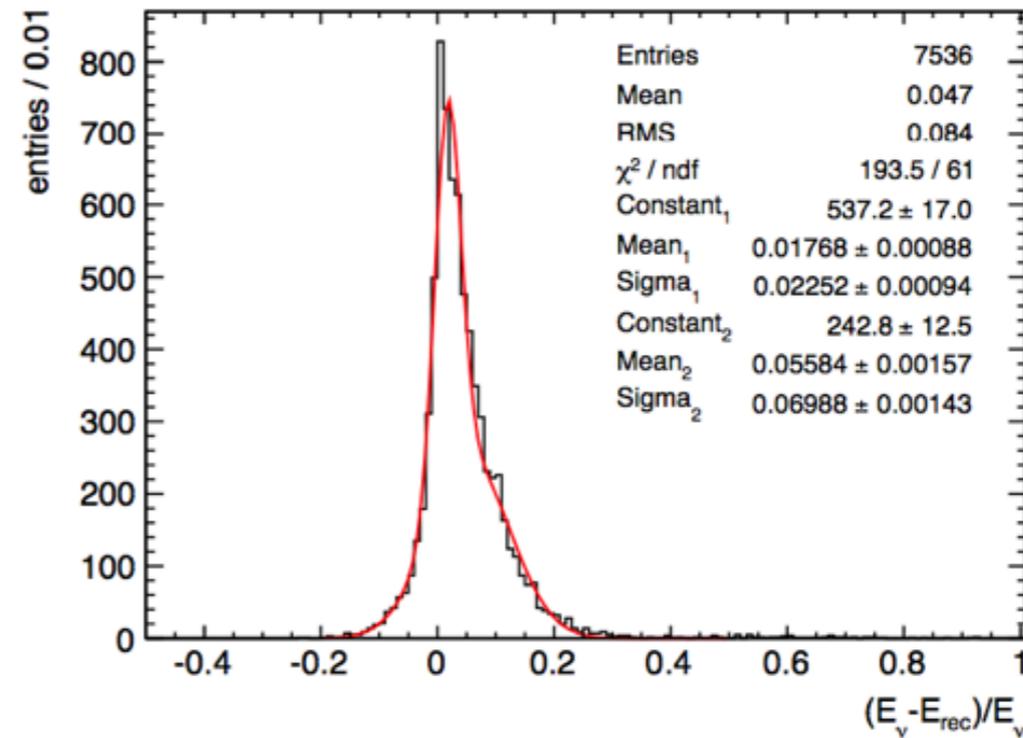
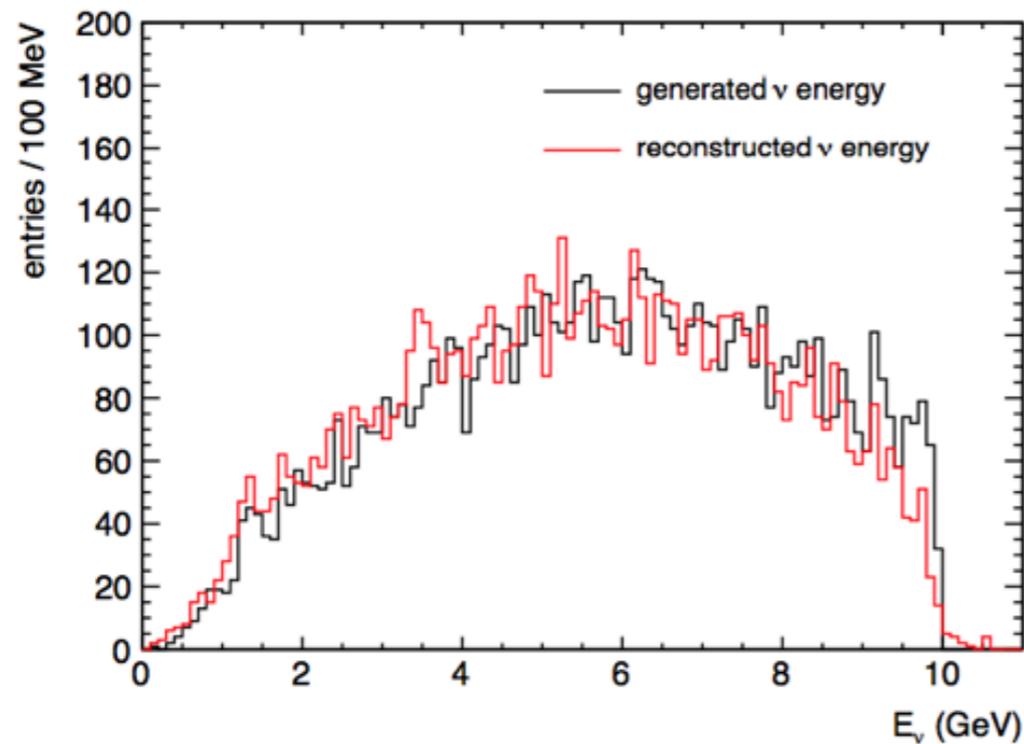


- ▶ **Besides its tracking capabilities, the liquid argon TPC is also a fine grained sampling calorimeter.**

- ▶ **Pioneering work** on LAr calorimeters was done by W. J. Willis and V. Radeka
“Liquid-argon ionization chambers as total-absorption detectors”, NIM 120, 221 (1974)

- ▶ **Principle:** All the energy of a particle is ideally converted into ionization through the development of the cascade showers, which is then drifted across a gap and readout electronically.

- ▶ **Limitations:**
 - ▶ particle leakage out of the surface of the detector (nuclear int. length = 83.6 cm, radiation length = 14 cm)
 - ▶ energy carried off by neutrinos
 - ▶ nuclear interactions releasing or absorbing binding energies
 - ▶ charge recombination
 - ▶ charge quenching of heavy nuclear fragments, alpha particles and nuclear evaporation products (saturation of response on densely ionizing particles)
 - ▶ electronic noise



- tracking done with GEANT4, including electron ion recombination
- event vertex placed in the center of the detector (all events are fully contained!)

$(E_\nu - E_{rec})/E_\nu$ RMS=8.4%